1 Digital Pulse Processor DPP3

The DPP 3.0 is equipped with KETEK's latest digital pulse processor DPP3, a high count rate and low-noise digital spectrometer designed for energy dispersive X-ray measurements using silicon drift detectors. In the following sections theory of operation, hardware design, implementation of digital signal processing, and instructions regarding the control of the DPP3 will be discussed.

1.1 Introduction and Theory of Operation

Digital pulse processors (DPPs) are used for signal evaluation of the detector output voltage in order to determine the X-ray energy spectra. Major steps for signal processing in DPPs include conditioning and digitization of the detector signal in an analog front-end, followed by application of digital filters, determination of pulse heights, and calculation of a multichannel analysis. Performance of the DPP3 has a major impact on the quality of acquired X-ray energy spectra, for example in terms of energy resolution and pile up rejection.

The KETEK DPP3 is optimized for operation with modern, high-performance silicon drift detectors using low-noise charge sensitive amplifiers (CSA). An example for a typical output signal of these detectors is shown in Fig. 1. Due to the reset of the feedback capacity within the CSA, a ramped voltage signal is generated. The DPP3 is designed to work with a ramped signal within the range -1 V to +1 V at the output of the preamplifier. As shown in Fig. 2 voltage steps superimpose the ramped signal when the SDD is irradiated with X-rays. Each of these voltage steps corresponds to an X-ray event detected by the SDD. Therefore, the voltage steps are also called X-ray pulses. Typical signal rise times of X-ray pulses depend in particular on the active area of the SDD and range from some ten to a few hundred nanoseconds. The amplitudes of X-ray pulses are proportional to the energy deposed by the photon within the SDD. In a typical setup using the KETEK DPP3 a voltage amplitude of 5 mV corresponds to an energy of about 1 keV ("gain" is 5 mV/keV). The count rate of X-ray pulses typically ranges from about 10,000 counts per second to about 1,000,000 counts per second, depending on the measurement application. However, the DPP3 is still capable of processing 4,000,000 counts per second with high throughput.

Fig. 1 Ramped preamplifier output signal

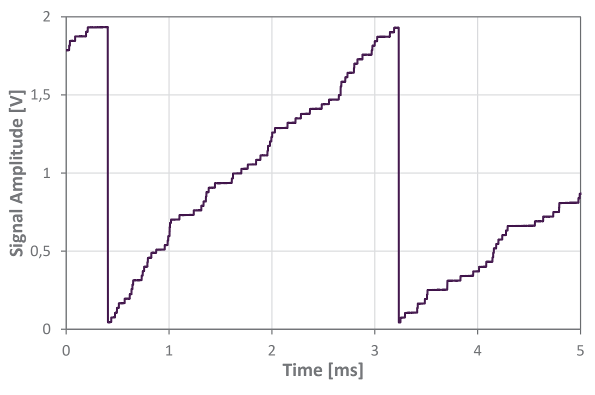
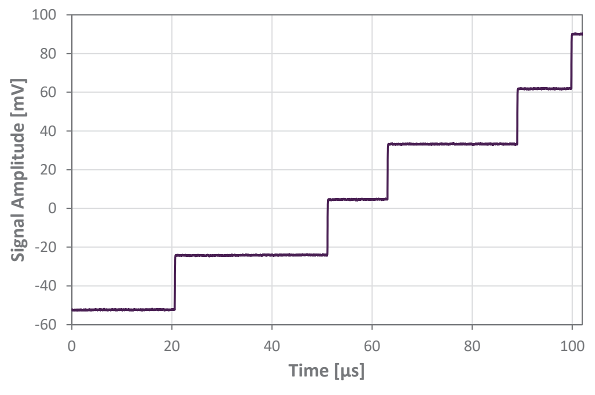


Fig. 2 Ramp signal with steps, marking X-ray radiation



Further highlight features of KETEK DPP3 are listed below:

- Ultra-short peaking times down to 25 ns allow operation at very high count rates with minimal dead-time.
- Modern high-speed interfaces: 100 Mbit/s Ethernet and Hi-Speed USB 2.0 for fast data readout as well as SPI interface for low-power board-to-board communication. SPI is recommended for hand-held instruments.
- VICOSoftware collection including comprehensive API (VICOLib) with programming examples, general purpose acquisition software (VICOScope) for Windows and Linux, and firmware update tool (VICOUpdate) available.
- Firmware update feature accessible to the user via any interface (Ethernet, USB, and SPI) for updates in field.
- Very small dimensions due to modern hardware architecture.

1.2 Hardware Description

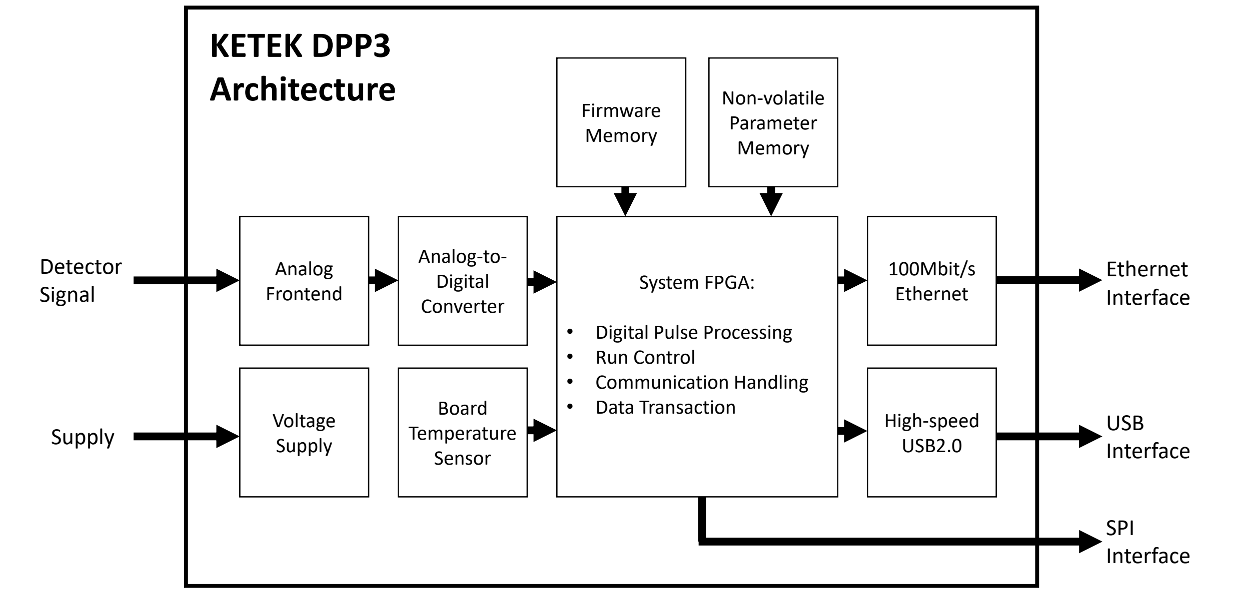
In this section a brief description of the KETEK DPP3 will be given. Fig. 3 on page 3 shows a functional block diagram of the DPP3. The preamplified detector signal is received via the VIAMP connector. In order to properly interface the analog-to-digital-converter (ADC) the detector signal conditioning is done within an analog front end of the DPP3. This low-noise analog circuit offers appropriate buffering, low-pass filtering, offset shifting, and single-ended to differential conversion with minimum temperature drift. Unlike most digital pulse processors on the market the DDP3 is not using a high-pass filter on the analog front end for AC-coupled digitalization of the detector signal. This enhanced pulse processing efficiency in applications with both, high count rates and high X-ray energies. Excellent energy resolution is achieved using a high-performance ADC. Key parameters of the ADC are a resolution of 16 bit, a sampling frequency of 80 MHz, low intrinsic noise, and very high linearity.

Digitalized signal data are read out by the system FPGA and digital pulse processing is done within the FPGA firmware. Major step is application of digital filters to the signal, pulse detection and determination of pulse heights using this filters as well as calculation of the multichannel analysis (MCA). A more detailed description of the digital pulse processing algorithms will be given in the following section „1.3 Digital Signal Processing“. Further tasks carried out by the FPGA firmware include the run control (i.e., starting and stopping MCA data acquisition), handling of host communication (i.e., processing of requests sent by the user), and data transactions (e.g., readout of MCA data). The KETEK DPP3 offers three different interfaces for communication between the host and the system FPGA: 100 Mbit/s Ethernet, Hi-Speed USB 2.0 and SPI. Ethernet and USB both use external controllers on the circuit board, while SPI is directly implemented in the FPGA firmware.

Please note the following specifications of the USB interface:

- Support of 480 Mbit/s “Hi-Speed” and 12 Mbit/s “Full Speed” USB 2.0.
- USB suspend/resume and remote wakeup are supported. When the device is suspended (e.g., no USB cable connected) a USB power saving mode is entered.
- KETEK vendor ID 0x20BD and product ID 0x0002 is used.
- USB device driver is available for automatic installation via Windows update (Windows 10 and newer). Also, the DPP3 USB driver files can be installed via KETEK software installer or provided by KETEK for manual offline installation.

Fig. 3 Functional Block Diagram of the DPP3



A further hardware component also shown in Fig. 3 is a board temperature sensor which is placed near the analog front end of the DPP3. The user can read out the current DPP3 board temperature acquired by this sensor via all communication interfaces. Furthermore, two non-volatile memory chips are connected to the FPGA. One firmware memory chip is capable of parallel storage of two FPGA firmware files in order to boot the FPGA at power-up. The utilization of this firmware memory chip for in-fields updates of the FPGA firmware is described in section „1.4.4 Update of the DPP3 firmware“ on page 22. The second memory chip is used for non-volatile storage of parameter settings. Two complete parameter sets are stored in this memory chip. The utilization of this parameter set memory chip for parameter set storage is described in section „1.4.3 Parameter Data Concept“ on page 21.

1.3 Digital Signal Processing

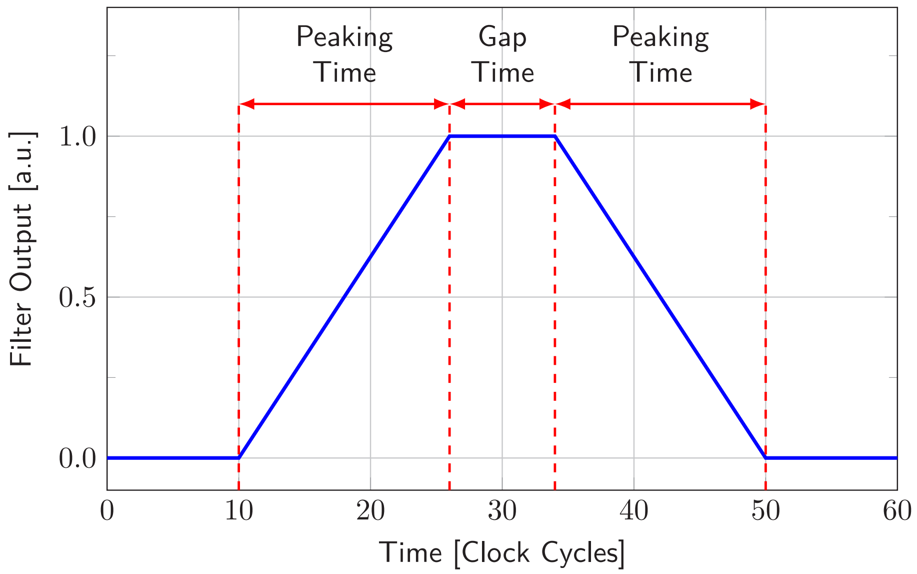
In the following an overview about digital signal processing for energy dispersive x-ray measurements using silicon drift detectors will be given. Theoretical considerations and practical implementation in the KETEK DPP3 will be covered. Goal is to give a basic understanding regarding digital signal processing and the influence of the DPP3 parameters on the spectroscopic results as those can be adjusted by the user in order to optimize the performance for a specific application.

1.3.1 Digital Filters

After digitalization of the amplified detector signal using an ADC, digital signal processing is done in a computing FPGA unit. First step of the pulse processing is the application of filters to the signal. This, so-called pulse shaping filters, are applied in order to improve signal-to-noise ratio and transfer the signal into a time domain waveform that allows a simplified evaluation. Historically, these shaping filters have been realized with analog RC-circuits prior to analog-to-digital conversion. However, nowadays these filters are implemented digitally after analog-to-digital conversion. Advantages of the digital pulse shaping are improved flexibly regarding the length (e.g., adjustability via software) and the waveform (e.g., more complex and selective filter designs) of the filters as well as a higher stability (e.g., no temperature drifts or aging as in analog RC-circuits).

Beside the optimization of the signal-to-noise ratio, the pulse shaping filters need to fulfill several constraints regarding their time-domain transfer function. Indispensable properties of the filter are a flat-top in the signal response in order to avoid ballistic deficits, finite filter duration to minimize pile-up effects, and zero area to guarantee independence from DC signals. The most common type of filter in the field of digital pulse processing is the trapezoid filter which provides good reduction of white noise, fulfills the upper mentioned requirements, and can be implemented very efficiently in digital electronics. Due to the good suppression of white noise, digital pulse processors using trapezoid filters are able to achieve good energy resolutions at short filter lengths. Calculation of digital trapezoid filters can be interpreted as the difference of two moving averages of the same length in a certain temporal distance. Fig. 4 shows the ideal step response of a digital trapezoid filter and the definition of two important filter time constants, which both have a major influence on the digital pulse processing: The peaking time is the length of each moving average. In the ideal step response of the filter the peaking time is the rise time of the filter output from zero to maximum value. The gap time is the temporal distance of the two moving averages. In the ideal step response of the filter the gap time equals the length of the flattop. In literature the gap time is also known as called flattop time.

Fig. 4 Ideal step response of a digital trapezoid filter



Typically, in modern digital pulse processors at least two digital trapezoid filters are calculated in parallel. A so-called fast channel filter (also called fast filter) which uses short time constants in order to achieve a good temporal resolution and a so-called slow channel filter (also called slow filter) which uses longer time constant in order to achieve good noise rejection. Utilization of these filters within the digital pulse processing will be described in the following sections.

1.3.2 Pulse Detection

A main task within the digital pulse processing is the detection of X-ray events within the detector signal. Main challenge hereby is the distinction between random signal fluctuations due to electronic noise and actual X-ray events. Typically, the pulse detection is realized using a discriminator within the fast channel. In case the fast filter output exceeds a defined trigger threshold an X-ray event is detected and further event processing is initiated. Depending on the application, a proper trigger threshold value must be found that gives a suitable distinction between random noise and desired X-ray events.

An important task of the pulse detection is the detection and rejection of so-called pile-up events. Pile-ups are a fast sequence of two or more successive X-ray pulses that cannot be resolved by the pulse processing. In case these pile-up events are not rejected by the pulse detection, wrong X-ray energy values will be introduced into the spectrum since the energy determination sees the sum or a fraction of the sum of multiple X-ray pulses. A simple but very effective method of pile-up rejection is the verification of time intervals between successive X-ray pulses in the fast channel. Successive X-ray pulses need to be detected in a certain temporal distance from each other in order to pass this pile-up criterion. The minimum acceptable temporal distance of successive X-ray pulses is given by the length (peaking time and gap time) of the slow filter. With higher slow filter lengths, a higher temporal distance of successive X-ray pulses is needed in order to avoid a pile-up event. This is the main reason why signal throughput is lower at higher peaking and gap times of the slow filter. The KETEK DPP3 uses this basic pile-up criterion at any time. No parameter adjustments are needed for this basic pile-up criteria since the DPP3 will set up the criterion automatically depending on the fast filter peaking time, slow filter peaking time, and slow filter gap time chosen by the user. For proper operation of this pile-up criterion, the fast filter peaking time should always be chosen to be equal or shorter than the slow filter peaking time to assure that fast channel achieves a better temporal resolution than the slow channel.

Despite the effectiveness of the former mentioned pile-up criterion, naturally there is a certain limit of its ability to detect pile-ups. In order to be able to reject a sequence of two or more successive X-ray pulses, the output of the fast channel has to fall underneath the trigger threshold of the pulse detection in between successive pulses. Only then the pulse detection recognizes the successive X-ray pulses as separates events and verifies their temporal distance. Therefore, the pile-up resolution time of this criterion is in the order of twice the fast filter peaking time. In order to further improve the pile-up rejection by separating successive X-ray pulses that are even closer than this, a second pile-up criterion is used in the KETEK DPP3. For this criterion the time in which the fast filter output exceeds the trigger threshold is determined for every detected X-ray event. This time will be compared to a maximum time (also called maximum width) defined by the user. Detected X-ray events are rejected from energy determination in case the time over threshold exceeds the maximum width. The basic idea behind this second pile-up criteria is the fact that the time over threshold for a single X-ray event should be about twice the fast filter peaking time plus the 0%-100% rise time of the X-ray event. Therefore, the time over the threshold for a certain detector system should never exceed a certain maximum time that is given by the sum of twice the fast filter peaking time plus the slowest 0%-100% rise time of the detector system. In case the fast filter output exceeds the trigger threshold longer than this expected maximum time, the detected event must be a sequence of two or more successive X-ray pulses and therefore should be rejected. Therefore, a proper setting for the maximum width is the sum of twice the fast filter peaking time plus the slowest 0%-100% rise time of the detector system. Although this second pile-up criterion can successfully reject successive X-ray pulses with much shorter temporal distance than the first pile-up criterion, the user should take special care in choosing the maximum width parameter. Setting the value of the maximum width parameter too low results in the rejection of valid (not piled-up) X-rays and reduces the signal throughput, especially at high X-ray energies. A good practice is to start with a high value of the maximum width at which the second pile-up criterion is practically disabled (e.g., a maximum width of 1µs for a fast filter peaking time of 50 ns). In order to improve pile-up rejection, the user than can lower the maximum width step by step until sufficient pile-up rejection is achieved while the signal throughput (e.g., dead time and peak heights) is still similar to the initial high value of the maximum width.

A further task linked to the pulse detection is the detection of the pulsed detector reset. The pulse processing must be stopped during the detector reset itself and also for any settling time of the detector signal after the reset. In the DPP3 detector resets are detected by using a discriminator with a certain negative threshold in the fast channel. The pulse processing is stopped as long as the slope of the detector signal stays negative. Additionally, a user defined reset inhibit time is waited for until the pulse processing is re-enabled. Therefore, this additional reset inhibit time should be at least as long as any settling time of the detector signal after the reset. Please note that signal throughput at high count rates and high X-ray energies suffers for unnecessarily long reset inhibit times.

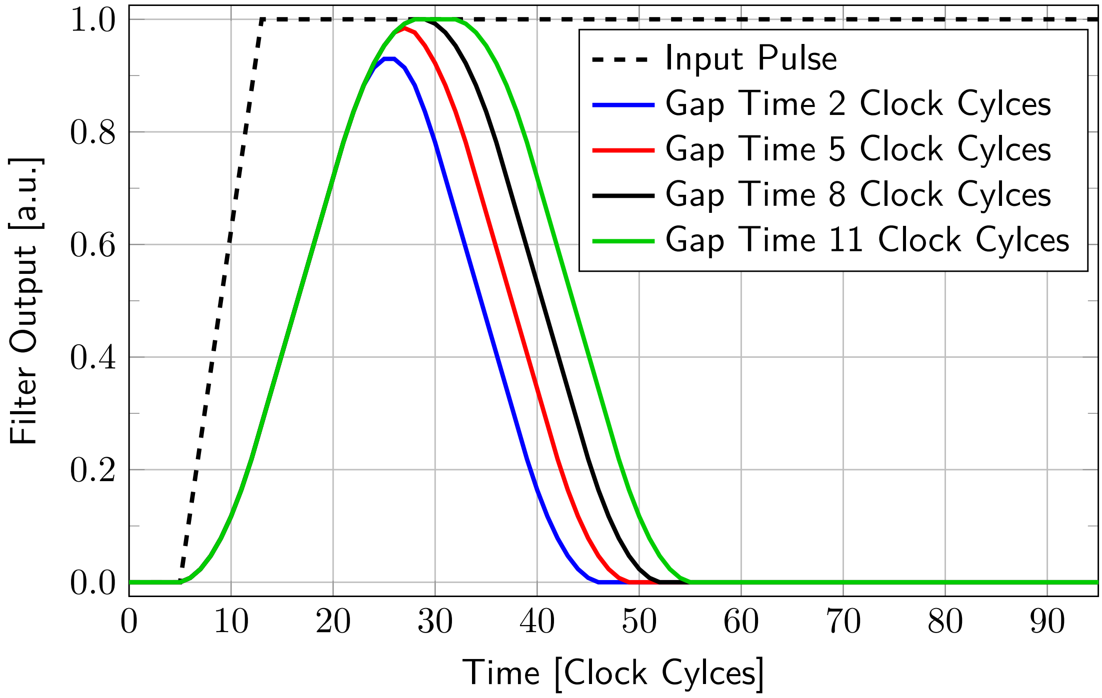
1.3.3 Energy Determination

The Task of energy determination is to precisely determine pulse amplitudes of X-ray events in the signal. Typically, this is done by extracting values from the output of the slow filter. The acquisition of an energy value is initiated by the pulse detection. In case the pulse detection indicates the detection of a valid X-ray event (e.g., passed both pile-up criteria and did not occur during reset inhibit time), a proper time window for the acquisition of the energy value within the slow channel is calculated. The starting point of this time window depends on the peaking times of fast and slow filter while the length of the time windows depends on the slow filter gap time. A raw energy value is acquired by finding the maximum value of the slow filter within the time window.

The noise level in the slow filter output has a direct impact on the noise associated with the acquired raw energy values and therefore strongly influences the energy resolution of the spectrum. Noise cancellation of the slow filter mainly depends on the spectral composition of the input noise and on the peaking time of the trapezoid filter. The typical spectral composition in signal processing with silicon drift detectors is mostly considered to be a superposition of white noise and low frequency noise. The strengths of the different terms mainly depend on properties of the detector (e.g., detector capacitance), the charge amplifier (e.g., transconductance), and on the detector temperature. Since the terms differ in their frequency dependence, in most cases an optimum peaking time which minimizes the overall noise can be found. However, in most applications not only the energy resolution, but also the signal throughput is a critical parameter in order to minimize spectrum acquisition times. Since short peaking times reduce the overall length of the energy filter, pile-ups and dead time can be minimized using peaking times shorter than the optimum for the best energy resolution. Choice of the peaking time in general therefore is a trade-off between noise reduction influencing energy resolution and filter length determining dead time.

Besides noise cancellation, a further challenge within energy determination is the minimization of the so-called ballistic deficit. In general, the term ballistic deficit refers to the reduction of the pulse amplitude during the shaping process. For the digital trapezoid filter ballistic deficit might occur due to the finite signal rise times of X-ray pulses. In order to prevent the loss of amplitude in the filter output, the gap time is introduced. Ballistic deficit can be removed by using a sufficiently high gap time to cover the total signal rise time. This is schematically shown in Fig. 5 on page 7. For an input unit step linearly rising within 8 clock cycles the outputs of different trapezoid filters are shown. All shown trapezoid filters use a peaking time of 16 clock cycles, but different gap times as states in the plot legend. For trapezoid filters with gap times shorter than the total rise time of the input signal the amplitude of the filter output does not cover the complete amplitude of the input step. In this case the energy determination sees a reduced pulse height and ballistic deficit effect occurs. For real X-ray pulses a total signal rise time often cannot be specified and ballistic deficit only can be minimized to a certain acceptable level. In case a detector has a fixed signal rise time for every pulse, the ballistic deficit effect might not be a serious problem since a constant fraction of amplitude is lost for every pulse. However, signal rise times of SDDs vary due to the different drift lengths in the active volume of the detector. Therefore, using an energy filter that does not prevent ballistic deficits causes a rise time dependency of the filter output height. Energy resolution and peak shape in the spectrum (low-energy “tailing”) suffer under these conditions due to rise time variations. A gap time in the energy filter has to be chosen to reduce these ballistic deficit effects to an acceptable level. However, it has to be considered that high gap times increase the length of the energy filter (see Fig. 4 on page 4) leading to a higher dead time. This is mostly significant when using short slow filter peaking times (e.g., 50 ns) since the gap time (e.g., 300 ns) can become the dominant part of the overall slow filter length. Therefore, the choice of the slow filter gap time in general is a trade-off between signal throughput and reduction of ballistic deficit effects and is also strongly influenced by the SDDs signal rise time distribution. A good starting point for the slow filter gap time is a value of 300 ns for SDDs with active areas of 7 mm² to 50 mm² and a value of 500ns for SDDs with active areas of 80 mm² to 150 mm². With these settings a strong reduction of the ballistic deficit effect can be achieved. For high-throughput applications using short peaking times and short slow filter gap times might be useful.

Fig. 5 Influence of the Gap Time



1.3.4 Baseline Correction

Another task within the signal processing is the correction of the baseline. The integration of detector leakage current in the charge sensitive amplifier causes the preamplifier voltage signal to rise, even in the absence of X-ray events. The amount of detector leakage current heavily depends on the detector temperature and on the size of the detector. The positive signal slope caused by the leakage current leads to a non-zero filter output of the slow filter, which also occurs in the absence of X-ray events. This offset in the slow filter output is called baseline. Energy values extracted from the slow filter output therefore are always the sum of X-ray pulse height and baseline value. In case the baseline value does not change over time, the baseline just introduces an offset in the spectrum that can be removed by energy calibration. However, in case of a baseline value drift (e.g., due to amplifier non-linearities or change in detector temperature) different energy values are affected by different offsets and spectra quality suffers irreversible (e.g., in terms of energy resolution). Therefore, in many applications baseline correction is desired.

Baseline correction aims at the subtraction of the baseline value from energy values extracted from the slow filter. The determination of the baseline value in done in absence of X-ray events. The absence of X-ray events is ensured by the pulse detection not indicating a triggered event within a defined time frame. In case this condition is fulfilled, baseline values are extracted from the filter output. Since the extracted baseline values are affected by electronic noise, a mean baseline value is calculated using multiple baseline samples. Without baseline averaging the subtraction of the baseline would add a significant level of noise to the energy value leading to a degeneration of the energy resolution. The amount of averaged baseline samples can be set via the parameter baseline average length. At a typical baseline average length setting of 256 the baseline mean value is calculated as average of the last 256 baseline samples extracted from the filter output. In general, high baseline average lengths offer a good reduction of the noise introduced with the baseline mean value. However, in case of a sudden change of the baseline a high baseline average length leads to a longer response time of the baseline mean value and the baseline corrections becomes less local. In modern high performance silicon drift detectors however, the baseline is very stable in most cases and a high baseline average length can be chosen.

Since the slow filter output needs a relatively long time to return to the baseline after an X-ray event occurred, the acquisition of baseline samples from the slow filter output is challenging at high count rates. Therefore, a good practice is not to extract baseline samples from the slow filter directly, but rather use a shorter filter for baseline determination. For shorter filters the acquisition probability for baseline samples increases and baseline corrections becomes more reliable. However, it should be noted that in general the baseline values from shorter filters are noisier and a higher level of baseline averaging is needed. The filter used for baseline sample acquisition is called medium filter in the DPP3 since the length of this filter usually is in between the fast and the slow filter. The length of the medium filter is chosen internally in the DPP3 depending on the slow filter peaking time. By default, the medium filter peaking time is set to about the quarter of the slow filter peaking time. However, at very short and very long slow filter peaking times there are some exceptions from this rule. With the logic set in the DPP3 a large majority of users do not have to deal with the length of the medium filter. However, in case an application needs special medium filter settings, the user can influence the medium filter peaking time by setting the baseline trim parameter. With this parameter the factor in between slow and medium filter peaking time can be influenced.

Also, the user has the possibility to completely disable the baseline correction. Under these conditions the DPP3 does not acquire baseline samples or calculate a baseline average value. Therefore, no offset subtraction from the energy values is done. This is mainly useful for debugging processes and is not recommended as default setting.

1.3.5 Dynamic Reset

The pulsed reset of the charge amplifier within the detector module is done using a fixed voltage threshold (e.g., determined by the input range of the ADC) in most systems on the market. The pulsed reset is applied to the charge amplifier in case the analog output voltage reaches the threshold. This basic reset circuit is also implemented inside the KETEK preamplifier. By default, this reset circuit ensures a ramped analog voltage output in a range of -1 V to +1 V. However, just using this basic way of triggering the pulsed reset of the charge amplifier is not the optimum solution when trying to minimize pulse losses due to the reset. Already at relatively low photon count rates the rise of the analog detector signal is dominated by X-ray pules while the rise due to the leakage current is neglectable in most cases. Therefore, when triggering the pulsed reset of the charge amplifier at a fixed voltage threshold in most cases an X-ray pulse will lead to the crossing of that voltage threshold. Since the voltage threshold already represents the upper limit of the ADC input range and since the reset is triggered almost immediately after the signal reaches the voltage threshold, evaluation of this last X-ray pulse is impossible in most cases. This effect is a major source of pulse losses due to the reset, since it occurs at practically each ramp cycle. These pulse losses are particularly relevant at high reset rates, caused by high X-ray energies and high counts rates.

In the combination of KETEK's DPP3 and generation 3 preamplifiers the digital pulse processing can influence the pulsed reset and a more sophisticated triggering of the reset can be used in order to minimize pulse losses. This method of pulsed reset triggering by the DPP3 will be called dynamic reset in the following. The basic idea of the dynamic reset is the definition of a new threshold voltage (so called dynamic reset threshold) that is below the fixed voltage reset threshold. The difference between dynamic reset threshold and upper limit of the ADC input range is chosen to equal approximately the rise of the highest energy X-ray pulse in a certain application. In case the signal voltage exceeds the dynamic reset threshold, the DPP3 will wait for the sum of slow filter peaking time and gap time and trigger the pulsed reset. As long as the amplitude of the X-ray pulse does not exceed the difference between fixed voltage reset threshold and dynamic reset threshold, this last X-ray event will still fit into the ADC input range. Also, due to the waiting time of slow filter peaking time and gap time there will be no loss of pulse amplitude of the X-ray. Therefore, in this way the digital pulse processing has the chance to successfully evaluate the last X-ray pulse before the reset. Although the ADC input range is not completely used in most ramp cycles, the utilization of the dynamic reset still is beneficially in almost every application since pulse losses due to the reset are reduces significantly. Utilization of dynamic reset can be enabled and disabled via the

DPP3 command set. Furthermore, user can set the dynamic reset threshold to optimize the dynamic reset method depending on the X-ray energy spectrum of a certain application.

1.3.6 Multichannel Analysis

The raw energy spectrum is generated by calculation of a multichannel analysis (MCA) of determined energy values. Therefore, a histogram of all valid energy values is calculated. The height of each channel corresponds to the number X-ray pulses counted within a range of energy values. The channels of the histogram are also called bins. The user can configure the number of bins used for the multichannel analysis depending on the needed dynamic range and granularity of the spectrum from 512 bins to 8192 bins. In addition, the KETEK DPP3 offers the possibility to set the data depth in terms of bytes per bin in the range of 1 byte per bin to 3 bytes per bin. Using a lower number of bytes per bin reduces the data size of the spectrum. However, at a lower number of bytes per bin the number of counts within each channel overflows already at lower values. For example, at 2 bytes per bin a maximum number of 2^(2*8)-1 = 2^16-1 = 65535 can be represented in each bin. If the counts within a bin are further increased from the maximum value of 65535, the channel overflows and the counts return to 0. Therefore, the user should choose the bytes per bin depending on the expected count rate and desired measurement time in order to prevent overflowing bins.

In many cases the user not only wants to set up the data size of the MCA but also wants to change the energy values associated with each bin. This can be done using the two parameters digital energy gain and digital energy offset. Every determined energy value will be multiplied with the digital energy gain before it is sorted into the spectrum. Therefore, large values of the digital energy gain will “stretch” and small values of the digital energy gain will “compress” the energy spectrum in the MCA data. Consequential large values of the digital energy gain will result in a lower eV/bin relation and small values of digital energy gain will result in a higher eV/bin relation. Together with the number of bins the digital energy gain also defines the maximum energy that fits into the MCA. When, for example, using an MCA with 8192 bins and a digital energy gain resulting in 5eV/bin the maximum energy in the MCA is approximately 5eV/bin * 8192 bins = 40960 eV.

Furthermore, a digital offset for energy values can be used. This offset is added to every determined energy value. An energy offset ranging from -256 bins to +256 bins can be set in the KETEK DPP3 in order to shift the energy spectrum within the MCA. The digital energy offset can be used to implement a 2-point energy calibration of the MCA on the device. Otherwise, a zero offset is the best choice in most cases.

Energy values that, after application of digital energy gain and digital energy offset, fall below the energy range represented by bin 0 are sorted into the lowest bin 0. Likewise, energy values that, after application of digital energy gain and digital energy offset, fall above the energy range represented by bin 8191 are sorted into the highest bin 8191. Please note that some energy values might are not be visible in the MCA if the number of bins is set to a lower value than 8192.

1.3.7 Measurement Statistics

In addition to the MCA described above the digital pulse processing calculates further measurement statistics that are often mandatory for analytic interpretation of the data. These measurement statistics of each spectrum run are:

- Real time: Time in seconds that has elapsed since the spectrum run started.
- Live time: Time in seconds in which the pulse detection was active during the spectrum run (fast filter below trigger threshold and no reset detected).
- Input counts: The total amount of events detected by the fast filter is called input counts.
- Output counts: The total amount of successfully evaluated events is called output counts.
- Input count rate: The input count rate (ICR) is an estimation of the X-ray photon rate in counts per

second and calculated as input counts divided by live time.

- Output count rate: The output count rate (OCR) indicates the rate of successfully evaluated events in counts per second and is calculated as output counts divided by the real time.

Using these run statistics, the dead time ratio can be calculated by the user as

Dead time ratio = 1 – OCR/ICR

The dead time ratio indicates the percentage of detected events that could not be evaluated (e.g., due to pile-up rejection or reset).

Each of the measurement statistics can be read out from the DPP3 using a specific function (e.g., VICOLib function getRunReal time for the real time). However, if each measurement statistic is read out on its own during an active run, there will be a time delay between the values. To overcome this challenge the DPP3 offers a command to read out all measurement statistics simultaneously (VICOLib function getRunStatistics). In this case all value measurement statistics are sampled at the same time and send to the user.

Please note that the live time is also stopped whenever the ADC is out of range since pulse detection cannot be active in this case. Therefore, the analog input signal should always maintain within the ADC digitalization range of -1 V to +1 V in order to avoid additional dead time. If an unexpected high dead time is observed it is recommended to use the oscilloscope feature of the DPP3 to verify the correct ramp position.

1.3.8 Parameter Optimization

Many applications require the optimization of a certain aspect regarding the spectra quality (e.g., energy resolution, low-energy performance etc.). In the following the most influencing DPP3 parameters for common optimization targets will be described.

1.3.8.1 Energy Resolution

The most obvious factor for improvements in energy resolution is the slow filter peaking time. As stated in „1.3.3 Energy Determination“ on page 6 the noise in the slow filter output directly affects the broadening of spectral lines due to electronic noise. In order to optimize energy resolution of the spectrum, choose a slow filter peaking time near the optimum. The optimum peaking time mainly depends on the detector type (e.g., type of charge amplifier) and detector temperature and for most setups is found around 1 µs to 2µs. In order to determine the optimum slow filter peaking time, the plot of energy resolution versus peaking time given in the datasheet of the detector can be used or own data using a measurement series can be acquired. However, please note that long slow filter peaking times increase pile-up effects and dead time rises. Therefore, choice of slow peaking time in general usually is a trade-off between energy resolution and signal throughput.

Under some conditions also the slow filter gap time can have a strong influence on the achieved energy resolution. This is especially the case if the slow filter gap time does not exceed the total signal rise times for some X-ray events and ballistic deficit occurs (see „1.3.3 Energy Determination“ on page 6). Under these conditions peaks in the spectrum form a low-energy tail and energy resolution suffers. Please note, that higher signal rise times can be seen for larger active areas of the detector and at higher detector temperatures. For a detector temperature of -35°C ballistic deficit effects usually are almost completely removed for a slow filter gap time of 300 ns for SDDs with active areas of 7 mm² to 50 mm² and for a slow filter gap time of 500 ns for SDDs with active areas of 80 mm² to 150 mm². By increasing the slow filter gap time above these values only minor further improvements of the energy resolution can be achieved. Similarly to the slow filter peaking time also longer slow filter gap times increase pile-up effects and dead time rises. This is mostly significant when using short slow filter peaking times (e.g., 50 ns) since the gap time (e.g., 300 ns) can become the dominant part of the overall slow filter length.

1.3.8.2 Signal Throughput

Optimal signal throughput in terms of output count rate (successfully evaluated events per time) in dependence of the input count rate is achieved at a dead time of 1-1/e ≈ 63%. In most applications however, input count rate is given and output count should be maximized (respectively dead time minimized) in order to achieve high statistics in the spectrum with minimum measurement time. This can be done most efficiently by reducing the length of the slow filter in terms of peaking time and gap time. Due to shorter filter length successive X-ray events with narrower temporal distance can be evaluated and losses due to pile-up rejection decrease. However, energy resolution in general worsens due to the reduction of peaking time (due to a higher level of electronic noise) and the gap time (due to a higher level of ballistic deficit). Therefore, choice of slow peaking time in general usually is a trade-off between energy resolution and signal throughput.

Another influencing factor of the signal throughput might be the pile-up rejection by the maximum width criterion („1.3.2 Pulse Detection“ on page 4). A strict setting of the fast filter maximum width might result not only in the rejection of pile-up pulses but also in the rejection of valid X-ray pulses. In this case the output count rate is decreased since a high number of X-ray events violate the maximum width criterion. A good starting point for a suitable fast filter maximum width is twice the fast filter peaking time plus the maximum total rise time of X-ray events. Short values of the fast filter maximum width should only be chosen in case the pile-up rejection is critical and some throughput losses due to this criterion are acceptable.

In case the energy spectrum contains a high portion of high energetic X-rays, also pulse losses due to the reset might become a significant issue for signal throughput. Under these conditions the dynamic reset utilization should be enabled and the optimal value for the dynamic reset threshold should be determined (see „1.3.5 Dynamic Reset“ on page 8) in order to minimize pulse losses due to the reset.

1.3.8.3 Pile-Up Rejection

In many applications a good performance of pile-up rejection is critical in order to get a “clean” spectrum with minimal distortions in terms of pile-up peaks and background caused by unresolved pile-ups. In this case it is useful to have a look at both pile-up criteria described in „1.3.2 Pulse Detection“ on page 4. For the second pile up criterion shorter values of the fast filter maximum width can be used to tighten the pile-up rejection. However, it should be noted that low values of the maximum width parameter at some point will result in the rejection of valid (not piled-up) X-rays leading to a reduction of signal throughput, especially at high X-ray energies.

In order to optimize the strength of the first pile-up criterion described in „1.3.2 Pulse Detection“ shorter fast filter peaking times can be chosen. This improves the temporal resolution of the fast channel and therefore the ability to resolve pairs of successive X-ray pules. However, the disadvantage of shorter fast filter peaking times is a higher level of electronic noise in the fast filter output. Distinction between random signal fluctuations due to electronic noise and actual X-ray events becomes more difficult and, since higher fast filter trigger thresholds must be chosen, worsens the ability to detect low-energy X-rays.

1.3.8.4 Low Energy Efficiency

Especially applications dealing with light elements often require the detection of very low-energetic X-ray events. Depending on the present noise conditions and on the used parameter settings desired low-energetic peaks might be excluded from the spectrum since they are not (or only a fraction of the pulses) detected by the pulse detection. In this case the user can try to extend the low-energy range of the system by lowering the fast filter trigger threshold. Smaller signal fluctuations will already be interpreted as X-ray pulses and the detection efficiency of low-energy X-rays might improve. However, at some point a very low fast filter trigger threshold will lead to triggering of signal fluctuations caused by electronic noise. Under these conditions a zero-energy noise peak will arise in the spectrum and signal throughput will be reduced.

In case the user is not able to find a suitable setting of the fast filter threshold that offers both, sufficient low-energy performance and zero-energy noise peak prevention, a higher fast filter peaking time might be an option. Choosing a higher fast filter peaking time leads to an improved noise reduction of the pulse detection. Therefore, lower fast filter trigger thresholds can be used without triggering of electronic noise. Higher fast filter peaking times therefore offer an improved distinction between random signal fluctuations due to electronic noise and actual X-ray events. However, the downside of this setting will be the worsening of time resolution in the fast channel. With higher fast filter peaking time the ability of the fast channel to resolve and reject pile-ups therefore will be worse and a higher amount of unresolved pile-ups will be present in the spectrum.

1.3.8.5 High Energy Efficiency

Applications dealing with a large portion of high energy X-rays (e.g., 30 keV) often require an optimization of the detection efficiency. The detection efficiently at high energies is limited by the detector itself since the photon absorption probability lowers due to finite detector thickness as well as by the digital pulse processor. In order to optimize the high energy efficiency of the DPP3 it is useful to enable the dynamic reset method and find a suitable setting for the dynamic reset threshold. A good practice to choose an appropriate threshold for the dynamic reset is to first determine the highest X-ray energy present in a certain application (e.g., excitation energy of 40 keV). As a second step calculate the corresponding voltage of this energy using the KETEK default gain of 5mV/keV (e.g., 40 keV correspond to 200 mV) and convert to ADC codes of roughly 30 µV each (e.g., 200 mV correspond to about 6667 ADC codes). Subtract the calculated amount of ADC codes from 65535 and choose a threshold for the dynamic reset about 2000 ADC codes lower than the result (e.g., subtraction of 6667 from 65535 gives 58868 and a good dynamic reset threshold would be about 57000). Also, the dynamic reset threshold can be optimized empirically for a certain application. In this case variate the dynamic reset threshold until the value is found at which the maximum output is achieved.

Another parameter of the DPP3 influencing the high energy efficiency might be the maximum width of the fast filter. The second pile up criterion described above might reject valid (not piled-up) X-rays pulses and lead to a reduction of signal throughput as a result, if the fast filter maximum width is set too low for the given rise time distribution of the detector. Since the width of the fast filter output also slightly rises with higher X-ray energies, this signal throughput degradation primary occurs at high X-ray energies.

1.4 Control of the DPP3

1.4.1 Overview

In order to provide easy control of the KETEK DPP3 the VICOSoftware collection was developed and includes an API with multiple programming examples for fast integration of the DPP3 control into customers software as well as graphical user interface, tools for general-purpose control and firmware updates. Using the VICOSoftware collection is the recommended way to control the KETEK DPP3 via USB or Ethernet interface as it is well-tested, safe and easy to implement.

However, it is also possible to control the KETEK DPP3 directly on a “low-level” protocol without using the abstraction provided by the VICOSoftware. In this case, the user has to send and receive command data via the respective interface. This kind of communication is in general more complex to implement as the user has to take care of correct command syntax, data interpretation and error handling. However, the low-level communication is the preferred way to control the KETEK DPP3 for some applications with special demands (e.g., very fast data readout) or in case the SPI interface is used.

In the following general information regarding the KETEK DPP3 control will be described, which apply for both VICOSoftware and low-level communication.

1.4.2 Parameters of the KETEK DPP3

The KETEK DPP3 is configured by setting the parameter values. Also, data and status information can be read out by obtaining parameter values. This is valid not only for the digital pulse processing functionality (e.g., peaking time) but also for system information data (e.g., firmware version or board temperature), communication settings (e.g., network IP address), and process control (e.g., start a run). In the following the most important parameters of the KETEK DPP3 will be described. All of these parameters are accessible via VICOSoftware over corresponding C++ functions as well as directly via low-level communication.

1.4.2.1 Run Control

The following parameters are related to the acquisition and readout of MCA data in a measurement run:

- Run Start:
  Calling this parameter starts the acquisition of MCA data with the current parameter settings. Please note that some parameter values are protected from changes during an active MCA acquisition run. In this case parameter changes will be declined after a run was started.
- Run Stop:
  Calling this parameter stops the acquisition of MCA data.
- Stop Condition Type:
  The stop condition can be used to automatically stop MCA data acquisition when a certain criterion is met. This parameter configures the type of automatic stop criteria:
  - None: Disables automatic stop of MCA data acquisition.
  - Stop at fixed input counts: MCA data acquisition is stopped when a fixed number of input counts is reached.
  - Stop at fixed live time: MCA data acquisition is stopped when a fixed live time is reached.
  - Stop at fixed output counts: MCA data acquisition is stopped when a fixed number of output counts is reached.
  - Stop at fixed real time: MCA data acquisition is stopped when a fixed real time is reached.
- Stop Condition Value:
  The stop condition can be used to automatically stop MCA data acquisition when a certain criterion is met. This parameter configures the value of automatic stop criteria:
  - If parameter “Stop Condition Type” is set to None: This parameter has no influence since automatic stop of MCA data acquisition is disabled.
  - If parameter “Stop Condition Type” is set to stop at fixed live time or stop at fixed real time: This parameter sets the live time or real time at which the MCA data acquisition is stopped.
  - If parameter “Stop Condition Type” is set to stop at fixed input counts or stop at fixed output counts: This parameter sets the input or output counts at which the MCA data acquisition is stopped.
- Get Run Statistics:
  Reads out measurement statistics of the current run. Run status (run active or not), real time, live time, output counts, input counts, output count rate, and input count rate can be read out individually or all at once.
- Get MCA Data:
  Reads out multichannel analysis (MCA) data of the current run. MCA data are returned as a data array. Size of the data array is defined by the parameters “MCA Number of Bins” and „MCA Bytes per Bin“. MCA data transmissions starts at the LSByte of Bin 0 and ends with the MSByte of the last bin.
- MCA Number of Bins:

Adjusts the size of the spectrum by setting the desired number of bins/channels used in the multichannel analysis (MCA). At a higher number of bins, the spectrum is more fine-grained and covers a wider energy range. However, data size and statistical errors increase with a higher number of bins.

- MCA Bytes Per Bin:
  Adjusts the data depth used in each bin/channel of the multichannel analysis (MCA). A higher data depth allows the representation of larger values (e.g., 2^(3*8)-1 = 16777215 for 3 bytes per bin) before the bin overflows. However, data size increases with a higher number of bytes per bins.

1.4.2.2 Pulse Processing

The following parameters configure the X-ray pulse processing functionality of the KETEK DPP3.

- Fast Filter Peaking Time:
  Adjusts the peaking time of the fast filter. Since the fast filter is normally used for pulse detection, short peaking times can be used to improve pile-up rejection. However, detection efficiency of low energy X-rays might suffer at short fast filter peaking times.
- Fast Filter Gap Time:
  Reads out the gap time of the fast filter. Since prevention of ballistic deficit in the output of the fast filter is not necessary, the fast filter gap time is always zero.
- Medium Filter Peaking Time:
  Reads out the peaking time of the medium filter. The medium filter peaking time is determined by the current setting of the slow filter peaking time and the parameter baseline trim.
- Medium Filter Gap Time:
  Reads out the gap time of the medium filter. Since prevention of ballistic deficit in the output of the medium filter is not necessary, the medium filter gap time is always zero.
- Slow Filter Peaking Time:
  Adjusts the peaking time of the slow filter. Since the slow filter is used for determination of X-ray energies, this parameter has a major influence on energy resolution and signal throughput. Typically, a longer slow filter peaking time improves the energy resolution at the cost of increased dead time.
- Slow Filter Gap Time:
  Adjusts the gap time / flattop time of the slow filter. The gap time of the slow filter is used to minimize ballistic deficit effects caused by the finite rise time of X-ray events. Long gap times offer an effective reduction of ballistic deficit effects (preventing e.g. the degradation of energy resolution and low-energy tail of peaks). However, a long gap time increases the length of the slow filter and therefore causes an increased dead time.
- Fast Filter Trigger Threshold:
  Adjusts the trigger threshold for pulse detection done by the fast filter. X-ray events are detected when the fast filter output exceeds this trigger threshold. Therefore, the fast filter trigger threshold should be chosen as low as possible in order to detect low-energy X-rays. However, at very low values the fast filter output will exceed the trigger threshold not only for X-ray events, but also for random noise. In this case a significant zero energy noise peak rises in the spectrum and dead time is increased.
- Medium Filter Trigger Threshold:
  Adjusts the trigger threshold for pulse detection with the medium filter. In case medium filter pulse detection is enabled, X-ray events are detected when the medium filter output exceeds this trigger threshold. Therefore, the medium filter trigger threshold should be chosen as low as possible in order to detect low-energy X-rays. However, at very low values the medium filter

output will exceed the trigger threshold not only for X-ray events, but also for random noise. In this case a significant zero energy noise peak rises in the spectrum and dead time is increased.

- Medium Filter Pulse Detection Enable:
  Enables or disables utilization of the medium filter for pulse detection. If enabled the medium filter will be used instead of the fast filter for the detection of X-ray events. Typically, the medium filter has a higher length compared to the fast filter and therefore the detection of low energy X-rays can be improved.
- Fast Filter Maximum Width:
  Adjusts the maximum width of the fast filter. The maximum width is a secondary pile-up criterion using the duration/width of the fast filter output above the fast filter threshold. A detected X-ray is rejected in case this duration is higher than the defined maximum width. The maximum width should be at least twice the fast filter peaking time plus expected rise time of X-ray events. In order to disable this secondary pile up criteria a maximum width way above twice the fast filter peaking time plus maximum X-ray rise time should be chosen.
- Medium Filter Maximum Width:
  Adjusts the maximum width of the medium filter. The maximum width is a secondary pile up criteria using the duration/width of the medium filter output above the medium filter threshold. A detected X-ray is rejected in case this duration is higher than the defined maximum width. The maximum width should at least equal twice the medium filter peaking time plus expected rise time of X-ray events. In order to disable this secondary pile up criteria a maximum width way above twice the medium filter peaking time plus maximum X-ray rise time should be chosen. This parameter only has an influence if medium filter pulse detection is enabled.
- Reset Inhibit Time:
  Adjusts the time duration for which the pulse processing is disabled after each detector reset. Whenever a highly negative slope is detected in the detector signal the pulse processing is being disabled in order to prevent a degradation of the spectrum due to detector resets. When the slope of the detection signal becomes positive again, pulse processing stays additionally disabled for the duration of the chosen reset inhibit time. Therefore, reset inhibit time should exceed the time needed by the detector to settle into normal operation after the reset slope becomes positive again. However, long reset inhibit times lead to higher dead times, most significantly at high input count rates and high X-ray energies.
- Baseline Average Length:
  Adjusts the number of baseline samples used to calculate the running average of the baseline value. The baseline is the output of the slow filter during the absence of X-ray events. A running average of the baseline is calculated using baseline samples acquired from the medium filter output in-between X-ray events. Higher baseline average lengths reduce the noise introduced by baseline correction and might improve the energy resolution. However, the reaction time to changes in the baseline (e.g., due to change in detector temperature) worsens at high baseline average lengths. In most cases a high baseline average is the best choice.
- Baseline Trim:
  Adjusts the baseline trim setting which determines the length of the medium filter. Long medium filters provide less noisy baseline samples and reduce the need of baseline averaging. However, long medium filter can acquire baseline samples less frequently than a short medium filter because it takes longer to return to the baseline after an X-ray event. In most cases an intermediate medium filter is the best choice.
- Baseline Correction Enable:
  Enables or disables utilization of baseline correction. The baseline is the output of the slow filter during the absence of X-ray events. Main cause of a non-zero baseline is the presence of detector

leakage current. When the baseline correction is enabled the current baseline average value is subtracted from each determined X-ray energy in order to eliminate the offset caused by detector leakage current. In most cases the utilization of the baseline correction is beneficial.

- Digital Energy Gain:
  Adjusts the digital gain for energy values. Every determined energy value will be multiplied by this gain. Therefore, large values will “stretch” and small values will “compress” the energy spectrum in the MCA data. Examples are shown in Tab. 3 below:

Tab. 3 Correlation Digital Energy Gain Settings and MCA Bin Width

Value of Digital Energy Gain	Approximate MCA Bin Width
1365	20 eV per bin
2730	10 eV per bin
4096	6.7 eV per bin
5461	5 eV per bin
10922	2.5 eV per bin

Please note that the exact value of eV / bin for a certain digital energy gain depends on the specific analog gain of the detector and preamplifier, thus might slightly differ due to component tolerances.

Together with the parameter “MCA Number of Bins” the digital energy gain also defines the maximum energy that fits into the MCA. Example: When using an MCA with 8192 bins and a digital energy gain of 5461, the maximum energy in the MCA is approximately 5eV/bin * 8192 bins = 40960 eV.

- Digital Energy Offset:
  Adjusts the digital offset for energy values. This offset it added to every determined energy value. A value of 32768 equals to zero offset, a value of 0 equals to the maximum negative offset of 256 bins and a value of 65535 equals to the maximum positive offset of 256 bins. This parameter can be used to implement a 2-point energy calibration of the MCA on the device. Otherwise, a value of 32768 (zero offset) is the best choice in most cases.
- Dynamic Reset Enable:
  Enables or disables utilization of dynamic reset. When enabled the DPP3 triggers the detector reset when the detector signal reaches the voltage set by the parameter “Dynamic Reset Threshold” and no X-ray event is currently processed. In most cases the detection efficient for high energy X-rays can be improved by enabling the dynamic reset.
- Dynamic Reset Threshold:
  Adjusts the threshold for the dynamic reset. When the dynamic reset is enabled by the parameter “Dynamic Reset Enable” the DPP3 triggers the detector reset when the detector signal reaches the voltage set by this parameter. The threshold voltage is set as ADC Code. The minimum code 0 corresponds to a signal voltage of about -1 V and the maximum code 65535 corresponds to a signal voltage of about +1 V. Therefore, each code represents about 30 µV.

  A good practice to choose the appropriate threshold for the dynamic reset is to first determine the highest X-ray energy present in a certain application (e.g., excitation energy of 40 keV). As a second step calculate the corresponding voltage of this energy using the KETEK default gain of 5 mV/keV (e.g., 40 keV correspond to 200 mV) and convert to ADC codes of 30 µV each (e.g., 200 mV correspond to about 6667 ADC codes). Subtract the calculated amount of ADC codes from 65535 and choose a threshold for the dynamic reset about 2000 ADC codes lower than the result (e.g., subtraction of 6667 from 65535 gives 58868 and a good dynamic reset threshold would be about 57000). Using this method, a threshold for the dynamic reset can be found which still allows the detection of the highest X-ray energy prior to the detector reset.

Also, the dynamic reset threshold can be optimized empirically for a certain application. In this case the dynamic reset threshold should be varied until the value is found at which the maximum output count rate is achieved. In most cases a suitable value is found in the range of 50000 to 60000.

- Dynamic Reset Duration:
  Adjusts the duration of the dynamic reset output signal generated by the DPP3 and sent to the preamplifier. The duration of the reset signal must be sufficiently long in order to be recognized by the preamplifier. In most cases a value of 200 ns is a good choice.
- Reset Detection:
  Reads out the detector type for reset detection. Since different detector types (e.g., CSA, CLD, CPC class) have different needs for reset detection, this parameter should be set depending on the used detector type.

1.4.2.3 Hardware and Diagnostic

The following parameters are related to hardware setup and diagnosis features.

- Parameter Set Load:
  Calling this parameter loads a parameter set from the non-volatile parameter memory into the working copy. See „1.4.3 Parameter Data Concept“ on page 21 for more details.
- Parameter Set Save:
  Calling this parameter saves the current working copy parameter set into the non-volatile parameter memory. See „1.4.3 Parameter Data Concept“ on page 21 for more details.
- Firmware Version:
  Reads out the firmware version number of the currently booted DPP3 firmware. The firmware version consists of a major, minor, patch, build and variant number.
- MCU Pass-through:
  Calling this parameter initiates communication to the MCU. This parameter is only meaningful for low-level communication. In the VICOSoftware all accessible MCU datagrams are implemented as separate functions. In this way the MCU Passthrough is abstracted in the VICOSoftware.
- MCU Status:
  Reads out the MCU status flags PWR, RDY, and ARDY
- Board Temperature:
  Reads out the PCB temperature of the DPP3 obtained by a temperature sensor near the analog front-end.
- Clocking Speed:
  Adjusts the clocking speed of the KETEK DPP3. Currently only 80 MHz is available.
- Analog Hardware Power Down:
  Enables or disables power down of the DPP3 analog signal front-end. In order to reduce power consumption when no measurement is active the analog hardware of the DPP3 (e.g., ADC and operational amplifiers) can be set to power down state. If this parameter is enabled the analog hardware is not powered.
- Event Trigger Source:
  Chooses the trigger source used when reading out signal traces using the oscilloscope feature. Options are:
  - ADC out of range: Triggers when an ADC out-of-range situation occurs (overvoltage or undervoltage at ADC signal input).

  - Active reset initiate: Triggers when a dynamic reset is initiated by the DPP3.
  - Fast filter pileup: Triggers when a pileup is rejected in the fast filter using the maximum width criteria defined by the parameter “Fast Filter Maximum Width”.
  - Fast filter reset detected: Triggers when a reset is detected in the fast filter.
  - Fast filter trigger: Triggers when an input count is detected in the fast filter.
  - Instant trigger: Trigger is activated instantly without any condition.
  - Medium filter pileup: Triggers when a pileup is rejected in the medium filter using the maximum width criteria defined by the parameter “Medium Filter Maximum Width”.
  - Medium filter reset detected: Triggers when a reset is detected in the medium filter.
  - Medium filter trigger: Triggers when an input count is detected in the medium filter.
  - New baseline sample: Triggers when a new baseline sample is acquired.
  - New output count of any energy: Triggers when a new output count of any energy is added to the MCA.
  - New output count of specific energy: Triggers when a new output count of a specific energy is added to the MCA. The specific MCA bin has to be defined using the parameter “Event Trigger Value”.
  - Specific ADC value: Triggers when a specific output value of the ADC is reached. The specific ADC code has to be defined using the parameter “Event Trigger Value”.
- Event Trigger Value:
  Adjusts the trigger value used when reading out signal traces with the oscilloscope feature. This parameter is used to define the specific ADC value or specific MCA bin in case the parameter “Event Trigger Source” is set to a specific ADC value or new output count of defined energy. If any other value is used for the parameter “Event Trigger Source” this parameter has no influence.
- Event Scope Sampling Interval:
  Adjusts the sampling frequency used when reading out signal traces with the oscilloscope feature. The signal traces have a fixed length of 8192 data points. By adjusting the sampling frequency using this parameter the number of signal samples obtained in one second can be chosen. Therefore, a suitable time base for the desired signal can be set up.

  The value of this parameter represents the factor of down-sampling regarding the 80 MHz system clock. Examples is shown in Tab. 4:

Tab. 4 Event Scope Sampling Interval Values

Value of Event Scope Sampling Interval	Sampling Frequency	Signal Length
1	80 MHz	102.4 µs
2	40 MHz	204.8 µs
10	8 MHz	1.024 ms
100	800 kHz	10.24 ms

  Please note that data collection for signal traces can take a considerable amount of time when using very low sampling frequencies.

- Event Scope Trigger Timeout:
  Adjusts the maximum waiting time for a successful trigger when reading out signal traces using the oscilloscope feature. In case the trigger condition set up by the parameters “Event Trigger

Source” and “Event Trigger Value” was not met during this time, a timeout error will be returned. Choosing a high timeout value is useful in cases where the trigger condition rarely occurs and a long maximum waiting time for the response (e.g., 16 seconds) is acceptable for the user.

- Get Event Scope:
  Reads out a signal trace using the oscilloscope feature of the KETEK DPP3. The oscilloscope feature is a diagnostic tool providing the possibility to capture and to display internal waveforms of the digital pulse processing. As a first step the user should set up the desired trigger condition (parameters “Event Trigger Source” and “Event Trigger Value”), sampling interval (parameter “Event Scope Sampling Interval”), and trigger timeout (parameter “Event Scope Trigger Timeout”). Afterwards the user can call this parameter in order to trigger the acquisition of one of the following internal waveforms:
  - ADC data
  - Fast filter output
  - Medium filter output
  - Slow filter output
  - Baseline average
  - Baseline samples

  The parameter will return 8192 signal data values in case the trigger condition was met during the trigger timeout time.
- Key Revision:
  Reads out the key revision version number for firmware encryption.
- Delete Firmware:
  Deletes the firmware in the update section of the DPP3 configuration memory (see „1.4.4 Update of the DPP3 firmware“ on page 22). This function must be unlocked using a proper service code. The time to get a response is typically between 30 and 75 seconds.
- Write Firmware Section
  Writes a section of firmware data in the given segment number of the DPP3 configuration memory (see „1.4.4 Update of the DPP3 firmware“ on page 22).
- Read Firmware Section
  Reads out a section of firmware data of the given segment number of the DPP3 configuration memory (see „1.4.4 Update of the DPP3 firmware“ on page 22).
- Service Code
  Adjusts the service code for maintenance access. This function is used to access KETEK-internal functions.

1.4.2.4 Communication

The following parameters configure the communication interfaces of the KETEK DPP3:

- Ethernet Power Down:
  Enables or disables power down of Ethernet hardware. In order to reduce power consumption when no Ethernet communication is needed (e.g., USB interface is used) the Ethernet interface can be set to power down mode. If this parameter is enabled the Ethernet hardware is not powered.
- Ethernet Protocol:
  Chooses the transport layer protocol used for Ethernet communication. Supported protocols are:

  - TCP: Transmission Control Protocol
  - UDP: User Datagram Protocol

  Please note that "Ethernet Apply" must be called for changes to become effective.

- Ethernet Speed:
  Chooses speed and duplex mode of the Ethernet communication. Options are:
  - Auto-negotiation: Uses auto-negotiation to determine Ethernet speed and duplex mode.
  - Full duplex 100 MBits: Forces Ethernet to run at 100 MBits/s and full duplex mode.
  - Full duplex 10 MBits: Forces Ethernet to run at 10 MBits/s and full duplex mode.
  - Half duplex 100 MBits: Forces Ethernet to run at 100 MBits/s and half duplex mode.
  - Half duplex 10 MBits: Forces Ethernet to run at 10 Mbit/s and half duplex mode.

  In most cases the auto-negotiation option is optimal. The Ethernet interface will automatically use the highest performance speed and duplex mode supported by each device present in the network. Forcing a specific Ethernet speed using other options than auto-negotiation can cause the communication to fail (e.g., due to network switches that do not support the chosen option). However, not using auto-negotiation might be useful in case power consumption is critical since 10 Mbit/s options draw significantly less power in comparison to 100 Mbit/s options.

  Please note that "Ethernet Apply" must be called for changes to become effective.

- Ethernet IP Address:
  Chooses the IP address used by the DPP3 Ethernet interface. Internet Protocol version 4 (IPv4) standard is used.

  Please note that "Ethernet Apply" must be called for changes to become effective.

- Ethernet Subnet Mask:
  Chooses the subnet mask used by the DPP3 Ethernet interface. Internet Protocol version 4 (IPv4) standard is used.

  Please note that "Ethernet Apply" must be called for changes to become effective.

- Ethernet Gateway IP Address:
  Chooses the gateway IP address used by the DPP3 Ethernet interface. Internet Protocol version 4 (IPv4) standard is used.

  Please note that "Ethernet Apply" must be called for changes to become effective.

- Ethernet Port:
  Reads out the port number of the Ethernet interface.

- Ethernet MAC Address:
  Reads out the hardware address (MAC) of the Ethernet interface. For the KETEK DPP3 the MAC address equals the device serial number.

- Ethernet Apply:
  Calling this parameter will apply the current parameter values of "Ethernet Protocol", "Ethernet Speed", "Ethernet IP Address, "Ethernet subnet mask", and "Ethernet gateway IP address" to the Ethernet interface. Please note that after calling this parameter any existing Ethernet connection with the device will be disconnected since the Ethernet interface is reconfigured.

- USB Power Down:
  Enables or disables power down of USB hardware. In order to reduce power consumption when no USB communication is needed (e.g., Ethernet interface of is used) the USB interface can be set to power down mode. If this parameter is enabled the USB hardware is not powered.

- SPI Power Down:
  Enables or disables power down of SPI interface. In case no SPI communication is needed (e.g., Ethernet interface of is used) the SPI interface can be set to power down mode. If this parameter is enabled the device is not accessible via SPI. SPI power down has practically no impact on power consumption. However, unintentional SPI communication can be prevented by disabling the interface.

1.4.3 Parameter Data Concept

In the following the management of parameter values in the KETEK DPP3 will be described.

1.4.3.1 Parameter Values in the Working Copy

Within the firmware of the KETEK DPP3 an overall amount of 256 different parameters are possible. Currently, not all of these 256 possible parameters are used since many are intended for future use. However, due to the size of the parameter memory, a complete configuration of the KETEK DPP3 consist of 256 parameter values. A complete configuration set of 256 values will be called a parameter set in the following.

When properly booted, the system FPGA always holds one parameter set in the volatile memory. All internal functions of the DPP3 (e.g., calculation of digital filters, network interface, …) use the parameter values present in this memory area. Therefore, this parameter set will be called working copy in the following. Whenever the user is reading out or changing parameter values using any of the communication interfaces, reading or writing operations are carried out at the working copy. In this way the user can read out or change the currently used parameter values.

1.4.3.2 Non-Volatile Parameter Values

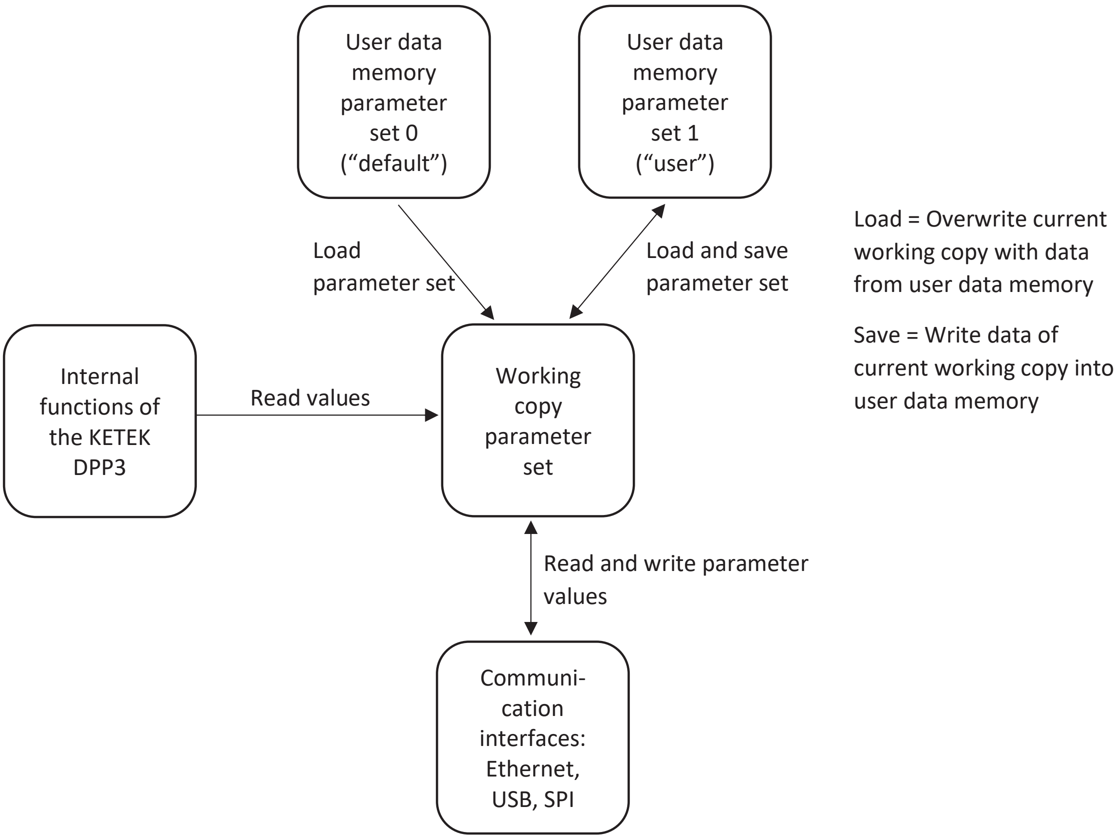
Since the working copy is stored in a volatile memory inside the system FPGA, the values are lost at every power cycle. In order to allow users to save settings in a non-volatile way, an additional memory device is included in the KETEK DPP3. This memory unit is referred to as "user data memory". The user data memory can exchange data with the system FPGA. The user data memory contains two complete sets of parameters (each with 256 values):

- Parameter set 0 of the user data memory is referred to as default parameter set. This parameter set will be written by KETEK during the production process. The user can load this parameter set, but he cannot overwrite the stored data. The default parameter set is meant to be a recovery option in case a faulty parameter set was created by the user.
- Parameter set 1 of the user data memory is referred to as user parameter set. This parameter set will be written by KETEK during the production process equally to the default parameter set. The user can load this parameter set and is also able to override the stored parameter set. The user parameter set is designed to allow the user to store preferred settings in a non-volatile way.

The user is not able to directly access the values in the user data memory. Instead, the user can initiate data exchange between the working copy and the user data memory using the parameters "Load parameter set" and "Save parameter set". Calling these parameters triggers the following functions:

- "Load parameter set": The current working copy is deleted and overwritten by the parameter values stored in the user data memory. When requesting "Load parameter set" the user can specify whether the default parameter set (parameter set 0) or the user parameter set (parameter set 1) should be transferred from the user data memory into the working copy.
- "Save parameter set": The current working copy is stored into the user data memory. When requesting "Save parameter set" the user can only choose the user parameter set and not the default parameter set since these data cannot be overwritten. Request of "Save parameter set" to the default parameter set will be declined by returning an error code.

The following diagram schematically shows the organization of parameter data described above:



When the KETEK DPP3 is powered, the user parameter set automatically will be loaded into the working copy. In this way the last settings saved by the user are available after each power cycle. Afterwards, the user might start changing the parameter values in the working copy via the communication interfaces and might save the changed parameter set in order to alter the settings used after the next power cycle.

1.4.3.3 Recovery to Default Settings

In case the user saved a faulty parameter set (e.g., all interfaces in power down or unknown IP address) into the user parameter set, a recovery to default settings might be necessary. In order to activate the recovery, the user must switch off the power of the KETEK DPP3 first. Activate the FPGA_DFLT input while powering the KETEK DPP3 (described below) and keep the input active at least for another three seconds. During the recovery process the user parameter set is overwritten with the values from the default parameter set. Therefore, after the recovery the user parameter set is identical with the default parameter set. As during the "normal" boot process in the following the user parameter set is loaded into the working copy, the user can now access the device with the default settings.

The FPGA_DFLT input can be activated by pulling pin 37 "FPGA_DFLT/MCU_REQFBL" of the electronics I/O connector to high (3.3V). When using KETEK Developer's Starter Kit with the breakout board EVICO-XV_3.0_ADAPT-L the FPGA_DFLT input also can be activated by pushing the mechanical button on the breakout board. Pushing the button on the breakout board will supply pin 37 "FPGA_DFLT/MCU_REQFBL" with 3.3V in order to carry out the recovery described above.

1.4.4 Update of the DPP3 firmware

The KETEK DPP3 provides the opportunity to update the DPP3 firmware using any communication interface (USB, Ethernet, SPI). This feature will be described in the following.

1.4.4.1 Firmware Memory Concept

The non-volatile firmware memory of the KETEK DPP3 is divided into two separate areas. Each memory area is capable of saving one complete firmware file. The firmware file in the first area will be called "golden image" while the firmware file in the second area will be called "update image":

- The golden image is stored into the firmware memory during the production process at KETEK. The latest DPP3 firmware version at the time of production will be used as golden image. The golden image cannot be modified using communication interfaces and can only be changed by KETEK.
- Usually no update image will be stored during the production process at KETEK. Therefore, this memory area is usually empty in delivery state. Using the communication interfaces a firmware file can be written into or read out from this memory area. Also, the update image can be deleted using the DPP3 command set. Please note, that in case a new firmware version was released in the time period between the production process and the delivery of the board, KETEK might write the new firmware release into the update image section prior to the delivery.

When the KETEK DPP3 is powered on, as a first step the device tries to boot using the currently stored update image. If the update image is bootable the startup sequence is finished at this point and the KETEK DPP3 is ready for operation. In case the boot sequence of the update image fails (e.g., no update image is stored or update image was corrupted) the KETEK DPP3 will instead boot using the golden image. Since the golden image cannot be modified in field, this firmware will always be bootable. The KETEK DPP3 is ready for operation using the firmware version stored in the golden image section.

Using this firmware memory concept, it is assured that the KETEK DPP3 still can be used after a failed firmware update attempt (e.g., power or communication loss during update). In this case the golden image is booted and the user can repeat the firmware update process or work with the golden image firmware version. In order to find out whether the golden image or the update image was booted, the user can read out the firmware version numbers.

1.4.4.2 Tools for Updating the Firmware

In order to update the firmware of the KETEK DPP3 via USB or via Ethernet the VICOUpdate tool is provided within the VICOSoftware for Windows and Linux operating systems. VICOUpdate can be controlled using a graphical user interface or using a command-line interface. With VICOUpdate a reliable firmware update can be done with a few clicks or commands. Using VICOUpdate is the recommended way of updating the firmware of the KETEK DPP3. In case the firmware update process should be integrated into the customer software and the VICOUpdate command-line interface cannot be used, the update process can also be implemented based on the VICOLib. In this case the functions deleteFirmware(), readFirmwareSection(), and writeFirmwareSection() can be used. More information on how to build a safe update process using these functions are available on request.

Furthermore, updating the firmware using low-level communication (USB or Ethernet communication but without VICOLib or SPI interface) is supported..