Verification of a novel calorimeter concept for studies of charmonium states
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Chapter 5. Signal analysis for PANDA EMC

As mentioned in the previous chapter, the PANDA EMC in the target spectrometer will be built with PbWO₄ (PWO) crystals [7]. The photo sensors are directly attached to the end face of the individual crystals and the preamplifier will be placed close to the photo sensor for optimum performance. To improve the light yield of PWO scintillators the EMC will be operated at a low temperature of -25 °C. Operation at low temperature also improves the noise performance of the preamplifiers. This helps to achieve the required large dynamic range of the front-end electronics. However, a placement of the electronics in the cold detector volume requires to minimize the power-dissipation of the preamplifiers.

The challenging requirements for the PANDA detector (Chapter 3) can only be met by a new approach to the data acquisition system (DAQ): the "trigger-less DAQ": the analog preamplifier signals will be continuously digitized by Sampling ADCs (SADCs). The system must be able to detect events and pre-process them on-line to extract and transmit only the physically relevant information. Due to mechanical constraints it is impossible to bring all analog signals outside the calorimeter volume, since the solenoid magnet only allows a limited space for feed-throughs. Therefore, the digitization module which digitizes the preamplifier signal will be placed inside the calorimeter volume but outside the low-temperature region [7]. Optical links will be employed to transfer the digitized data via a multiplexing stage in a fast and compact manner to the computer node.

It is impossible to store all the data produced by the digitizer modules. Therefore, only reduced information should be reported and stored, namely the energy and the time-stamp of each hit. To derive this information reliably and fast during data taking, i.e. “on-line”, for each incoming event, the so-called feature-extraction algorithm was developed in this work. This data-processing algorithm will be applied to the digitized data. Compared to an analog signal treatment by filtering and noise suppression, such a digital treatment allows more flexibility. By tuning the parameters of the digital signal-processing algorithm one can provide better results. This chapter will focus on the main readout electronics chain for the PANDA EMC, the preamplifiers, and the feature-extraction algorithm.

5.1 General EMC Readout Scheme

The readout scheme of the electromagnetic calorimeter contains the low-noise charge-sensitive preamplifier and shaper units, the digitizer module, and the data multiplexer (MUX). The concept of the readout scheme is depicted in Figure 5.1.

The low-noise charge-sensitive preamplifier, combined with a shaper stage, is placed in the cold area of the calorimeter and directly attached to the photo sensor. The digitizer modules are located at a distance of 20-30 cm and 90-100 cm for the Barrel EMC and the Forward Endcap EMC, respectively, [7] from the analog circuits and outside the cold volume. The digitizer modules consist of high frequency, low-power pipelined ADC chips.
[7], which continuously sample the amplified and shaped signals. The features of the individual signals are extracted in the digitizer module. The digital data are further transferred by optical-link connections to Data Multiplexer units which combine information from a few EMC-digitizers and transfer the data to a Compute Node. This is a FPGA-based processing unit for on-line data processing, e.g. cluster finding for the EMC and particle identification.

![Figure 5.1: The layout of the readout electronics for the PANDA EMC.](image)

### 5.1.1 Charge-sensitive preamplifier

As already mentioned in the previous Chapter, when an incident photon interacts with the detector material a shower of charged particles is produced which generates scintillation light and subsequently a charge signal in the photo sensor. For e.g. a Geiger-Müller tube and many scintillation counters, the amount of produced charge is large and the corresponding large voltage pulse can drive a long cable. In a semiconductor detector, however, the produced charge is small and it needs amplification. The first-step amplification element is called “preamplifier” [42]. The preamplifier is located close to the detector to prevent a capacitive loading. One function of the preamplifier is to terminate the capacitance quickly and, therefore, to maximize the signal-to-noise ratio. For this reason, the preamplifiers should be placed as close as possible to the detector. The rise time of the output pulse should be kept as short as possible, equivalent to the charge collection time in the detector. The decay time of the pulse is relatively long (20 - 100 µs) to allow full collection of the charge from the detector [42].

Preamplifiers can be either of the voltage-sensitive or charge-sensitive type. A schematic diagram of a voltage-sensitive configuration is shown in Figure 5.2. If the time constant of the input circuit is large compared to the charge collection time, then the input pulse amplitude is equal to

\[ V_{\text{max}} = \frac{Q}{C} \]  

(5.1)

where \(C\) is the input capacitance and \(Q\) is the produced charge. For most detectors the input capacitance is fixed, for example, in the case of a voltage-sensitive preamplifier the output pulse is proportional to the charge \(Q\) liberated by the incident radiation. However, in semiconductor detectors, the detector capacitance can change with the operating parameters.
In these situations, a voltage-sensitive [42, 43] preamplifier is undesirable since the fixed relationship between $V_{\text{max}}$ and $Q$ is not applicable anymore. For this case the charge-sensitive preamplifier is the best option.

![Figure 5.2: Schematic diagram of a simplified voltage-sensitive preamplifier with amplification $A$ of the operational amplifier. $R_1$ is the input resistance and $R_2$ is the feedback resistance. If $A >> R_2/R_1$, then $V_{\text{out}} = -V_{\text{in}} \cdot R_2/R_1$.](image)

The elements of a charge-sensitive configuration are shown in Figure 5.3. For this circuit, the output voltage is proportional to the total integrated charge in the pulse. The rise time of the pulse produced by the preamplifier is determined only by the charge collection time in the detector and is independent of the capacitance of the detector or preamplifier input.

For the PANDA EMC two different charge-sensitive preamplifiers have been developed: an ASIC (Application-Specific Integrated Circuit) preamplifier and a discrete-component preamplifier including a shaper unit, developed at GSI Darmstadt, Germany, and at University of Basel, Switzerland, respectively [7]. Here, we give a short functional description of these preamplifiers.

![Figure 5.3: Schematic diagram of a simplified charge-sensitive preamplifier with amplification $A$ of the operational amplifier. The time constant given by the product $C_f R_f$ determines the decay rate of the tail of the output pulse. $C_i$ is the input capacitance, $C_f$ the feedback capacitance, and $R_f$ is the feedback resistance [42]. If $A >> (C_f + C_i)/C_f$, then $V_{\text{out}} = -Q/C_f$.](image)

The Low-Noise Low-Power Consumption (LNP) preamplifier is a discrete charge-sensitive preamplifier [7], which was primarily designed for the LAAPD readout. The design was further developed for the readout of the vacuum photo-triode (VPT) for the
Forward Endcap EMC. The LNP was implemented in the prototype of the Barrel EMC for the readout of the Large-Area Avalanche Photo Diodes to study the performance in beam experiments. The LNP has excellent noise performance in combination with low power consumption. The LNP has a power consumption of 45 mW in the idle state, but the power dissipation is dependent on the event rate and the photon energy [7]. A reasonable maximum power consumption of ~100 mW can be presumed. To reach a low detection threshold, the noise performance of the preamplifier is very important. The noise of the LNP preamplifier with an input capacitance of 22 pF at -25 °C has a typical equivalent noise-charge (ENC) of 235 e⁻ [44].

![Figure 5.4](image)

**Figure 5.4:** The single-channel LNP preamplifier prototype circuit board and a typical output pulse shape. The pulse shape is recorded with a 100 MHz sampling rate and 16-bit resolution SADC.

The LNP preamplifier is designed for a single-pulse charge input of maximum 4 pC. The single-ended output of the preamplifier is designed to drive a signal on a 50 Ω line. The rise time and fall time (change of the signal from the 10% level to the 90% level) of the LNP preamplifier signals are 10 ns and 55 μs, respectively. Figure 5.4 shows a photograph of the preamplifier and the output pulse shape.

**ASIC APFEL preamplifier:** This charge-sensitive preamplifier and shaper ASIC APFEL (Asic Panda Front-End ELectronics) was developed for the readout of the avalanche photo diodes with a capacitance of 300 pF [45]. It has two independent channels with dual-gain output per channel. The gain ratio of 1:32 per single LAAPD was chosen to cover a large dynamic range from 10 MeV up to 12 GeV.

An overview of the readout stages is shown in Figure 5.5. A channel consists of a charge-sensitive amplifier (CSA), a pulse shaper and an output stage. The ASIC preamplifier and shaper will be placed in the Barrel EMC. The bulk of particles produced in the antiproton annihilations will be emitted in the forward direction and the hit rate in the Barrel EMC will be much less in comparison with the Forward Endcap EMC.

Therefore, the charge sensitive preamplifier output in the ASIC is connected to a shaper unit with 250 ns peaking time [46], in order to reach a better energy resolution due to a better charge collection. The ASIC chip will be placed on a specially designed Printed-Circuit Board (PCB) which is directly soldered to the LAAPD. The ASIC chip itself is protected by a 2×2 cm² large capsule made from PEEK material. The capsule will be attached to the end face of the PWO crystal. The output signal of the ASIC chip is connected via flat cable to a driver board. To get maximum performance, 10 cm length has been found.
as optimal length. The driver board has channels with different gain to cover the required dynamic range. The test board and the corresponding output pulse shape are shown in Figure 5.6.

![Figure 5.5: Concept of the ASIC preamplifier [46].](image)

Figure 5.6: Left: The ASIC-chip preamplifier board; Right: a voltage signal with the typical pulse shape [47].

### 5.1.2 SADC readout

For the data acquisition, the preamplifier output signals are digitized by Sampling Analog-to-Digital Converters (SADCs). The SADC takes samples of the continuous analog signal and converts these to a time series of digital values.

The application of an SADC is the best choice to prevent a high dead time of the detector, which might occur due to the expected high annihilation rate of \(2 \times 10^7 \text{annihilations/s} \). The digitized signal traces are stored to a buffer in a FPGA (Field-Programmable Gate Array) which is part of the digitizer module. The program-code, the so-called firmware loaded to the FPGA, can process the digitized signal and will provide the detected pulse features. An implementation of the feature extraction into an FPGA will be described in Chapter 7. For all test experiments, we have used a commercial SADC, the STRUCK SIS3302 module [48]. The SIS3302 module is an 8-channel ADC/digitizer board with a sampling rate up to 100 MHz for an individual channel and a resolution of 16 bit [48].
The SADC contains 5 SPARTAN FPGA from the Xilinx family. Four FPGAs process data from 8 ADC channels and one FPGA is controlling the VME interface. The main features of the SADC are the following:

- 8 channels;
- 16-bit resolution;
- 32 MSamples/channel memories;
- External clock range 1 - 100 MHz;
- Input bandwidth of 50 MHz;
- +5, +12V and -12 V VME standard voltages.

![Figure 5.7: SIS 3302 8-channel sampling ADC with 100 MHz sampling rate and 16-bit resolution.](image)

### 5.2 Data Acquisition

The VME-based Data AcQuisition system (DAQ) applied for the test experiments consists of a single “branch” within the GSI Multi-Branch System (MBS) framework [49].

The data sender is a RIO-3 [50] processor, which resides in the VME crate. The RIO-3 handles the readout of the digitizers (SADCs, Time-to-Digital Converters) and then passes the data via TCP/IP (transmission control protocol/internet protocol) to a Lynx-OS PC, which acts as data receiver. The latter formats the events and makes these available to analysis clients (e.g. via a remote event server) and controls taping or disk storage. For on-line visualization of the data stream, several different software packages can be used. For all our test measurements, we have used the GO4 program package for data analysis and visualization [51].
5.3 The feature-extraction algorithm

The charge-sensitive preamplifier output is directly digitized by the SADC. The direct digitization has some advantages in comparison with an analog signal-filtering approach in between. Applying digital signal processing tools to the digitized signal can provide a better performance, as already discussed above. Another disadvantage of analog filtering components is that they could be sensitive to environmental influences, e.g. temperature changes or magnetic fields, but the digital filter remains unaffected by such environmental influences [52].

To extract energy and time information of a digitized signal data-stream, digital filter processes are applied such as the Moving-Window Deconvolution (MWD), the Moving Averaging (MA), and the Constant-Fraction Timing (CFT). These are explained in the following:

**Moving Window Deconvolution:** The particle energy or energy deposition corresponding to the measured signal is usually obtained from the signal amplitude which is generated by an analog shaping preamplifier with a combination of integrating and differentiating circuits with time constants of a few µs. Equivalently, to extract the pulse amplitude from a digitized preamplifier signal, the MWD process is applied [53]. The MWD filter transforms the fast rising pulse with a long exponential tail into a rectangular shaped signal [54].

As mentioned above, the output of a charge-integrating preamplifier has a fast rise time of 10 ns and an exponential tail (fall time) of about 55 µs. The pulse provided by an ideal charge-integrating preamplifier should have a step-like shape, where the height of the step corresponds to the accumulated charge. However, the resistor in the feedback loop of the preamplifier continuously discharges the integrating capacitor. Therefore, the output pulse is a convolution of a step-like function with an exponential decay. To restore the original height of the step one needs to apply a deconvolution procedure. Let us consider a convoluted pulse \( f(t) \) starting at time of \( t_0 \) which is the time \( t = 0 \),

\[
A[f(t_n)] = A[f(t_n)] + A[f(t_n)] = A[f(t_n)] + A(1 - e^{-\frac{1}{\tau} t_n}) =
\]

\[
f(t) = \begin{cases} 0, & t < 0 \\ \frac{1}{\tau} t, & t \geq 0 \end{cases}
\]

where \( \tau \) is the signal decay constant and \( A \) the pulse amplitude. The amplitude \( A \) at time \( t_0 \) can be derived from

\[
A[f(t_n)] + A[f(t_n)] = A[f(t_n)] + A(1 - e^{-\frac{1}{\tau} t_n}) =
\]

\[
f(t_n) = \frac{1}{\tau} \int_{0}^{t_n} f(t) dt = f(t_n) + \frac{1}{\tau} \int_{-\infty}^{t_n} f(t) dt
\]

where \( n \) is the sample number. Since we are going to apply the MWD filter digitally to the digitized pulse it is useful to change from the continuous to the discrete expression:

\[
A[n] = x[n] + \frac{1}{\tau} \sum_{k=-\infty}^{\infty} x[k] = x[n] - (1 - \frac{1}{\tau})x[n-1] + A[n-1]
\]
The deconvolution equation 5.7 transforms the continuous-discharge preamplifier signal into a signal from a transistor-reset preamplifier, which is a stair-case signal. Applying a numerical differentiation to the discrete form of the deconvolution equation 5.7, we obtain the MWD equation

$$MWD_m[n] = A[n] - A[n-m] = x[n] - x[n-m] + \frac{1}{\tau} \sum_{k=n-m}^{n-1} x[k]$$

(5.9)

where \(m\) is the output pulse length given as the number of sample points\(^1\). The process of MWD filtering is illustrated in Figure 5.8. A deconvolution operation does not improve the signal-to-noise ratio [55]. Therefore, the noise contribution to the MWD signal is reduced by a subsequent low-pass filter.

![Figure 5.8](image)

**Figure 5.8:** Top: the raw preamplifier signal with a total pulse length of 55 µs, but for the MWD only a few sample points are needed after the rising edge. Bottom: pulse shapes obtained after the MWD (black histogram) and the combined filters MWD and MA (red histogram).

The **Moving Average (MA)** procedure is a filter algorithm in digital signal processing. A number of sample points from the input signal are averaged to produce each point of the output signal. This averaging action can remove the high-frequency components in the signal and it plays the role of a low-pass filter. The MA equation for this filter procedure reads as follows [55]

$$MA[n] = \frac{1}{L} \sum_{j=0}^{L-1} A[n+j]$$

(5.10)

\(^1\) For convenience, \(m\) is also occasionally used to indicate the deconvolution differentiation length in [ns], i.e. the number of sample points is multiplied by the length of the sampling interval.
where \( L \) is the number of sample points in the average\(^2\). The parameter \( L \) is usually equal to the integration time of the analog filter. Increasing the number of averaged samples can cause a decrease of the noise level. Figure 5.9 shows the variation of the noise level for different averaging lengths. We observe that the RMS width of the noise level can be reduced from 1 MeV (for the conventional electronics) down to 0.3 MeV.

The MWD procedure together with the MA filter provides the pulse shaping and the noise reduction of a digitized preamplifier signal. Tuning of the parameters of the MWD and MA algorithms can influence the obtained pulse shape. For an averaging length \( L \) equal to the deconvolution differentiation length \( m \) a triangular shape is generated, and if \( L \neq m \) a trapezoidal signal shape is generated. Defining \( \oplus \) as the operator for the combined application of MWD and MA filter, we obtain:

\[
T_L^m[n] = MA_L[n] \oplus MWD_m[n] \quad (5.11)
\]

Figure 5.9: The dependence of the noise level on the smoothing length \( L \).

The Forward Endcap EMC [7] will operate at high single-hit rates, up to 500 kHz. To avoid pile-up of different signals it is extremely important to keep the hit response of the single-crystal detector as short as possible. In order not to lose efficiency of the PANDA detector, the pileup probability of the PANDA EMC needs to be limited to 1% [7]. For the 500 kHz hit rate, this requirement demands a very short response time of the detector of about 20 ns. With the optimal shaping parameters for the highest energy resolution, namely with a differentiation time-constant of 200 ns, the pile-up probability will be \(~14\%)\), which is unacceptably high. Therefore, the detector response should be shortened while keeping the EMC energy resolution within the requirements defined by the physics program, namely below about 3%. The pulse shape of the LNP preamplifier, used in the Forward Endcap EMC, is shown in Figure 5.10. As described above, the MWD digital filter differentiates the incoming pulse and compensates for the exponential discharge of the integrating capacitor in the preamplifier. It was found that the resulting tail of the LNP preamplifier pulse, shaped by the MWD filter, has an exponential behavior.

\(^2\) For convenience, \( L \) is also occasionally used to indicate the smoothing length in [ns], i.e. the number of sample points is multiplied by the length of the sampling interval.
Therefore, such tail can be compensated by applying a second MWD filter with the corresponding decay constant. The resulting double MWD shaping of an LNP preamplifier trace is shown in Figure 5.10.

![Figure 5.10: LNP preamplifier pulse shape before (black solid line) and after single (red dashed line) and double (blue dash-dotted line) MWD filtering for 80 ns length (left) and 200 ns (right) differentiation time constants of the MWD filter [56].](image)

The double MWD filtering allows obtaining a much shorter pulse and recover its original amplitude for short differentiating time-constants without increasing the noise level. Figure 5.11 shows the recovery of the pulse amplitude after a second MWD filtering as a function of the differentiation time-constant of the first MWD filter. Only for the very short differentiation time-constants, below 80 ns, the pulse amplitude can not be completely recovered even though it provides a much higher amplitude than the single MWD filtering. Such a signal recovering technique allows to efficiently achieving a low triggering threshold while reducing the pulse width. In order to exploit this advantage, it is preferable to keep the pulse-amplitude recovery at the level of minimally 95%. The usage of the double MWD

![Figure 5.11: The pulse amplitude after single (red solid line) and double (blue dashed line) MWD filtering as a function of the differentiation time-constant of the first MWD filter [56].](image)
filtering does not influence the resulting energy resolution of the detector. Using signals from the tagged-photon measurements at 1 GeV (see Chapter 6.3.5), we observe in Figure 5.12 that the cluster energy resolution for γ rays is the same for the single and double MWD filtering [56]. For the Forward Endcap EMC, taking into account the above mentioned criteria for the energy resolution and the pulse-amplitude recovery, the double MWD filtering with the differentiation time-constant of about 60 ns will provide the best performance in terms of low pile-up probability without compromising the energy resolution of the detector.

![Figure 5.12](image_url) Measured cluster energy resolution for tagged photons of 1 GeV energy obtained using the single (red solid line) and double (blue dashed line) MWD filtering method. The energy resolution is plotted as a function of the differentiation time-constant of the first MWD filter [56].

The **Constant Fraction Timing (CFT)** algorithm is applied to extract the precise time information from the measured signal. This signal time-stamp can be used to correlate particle signals to specific events. As mentioned before [7], for the precise event-time determination and random background suppression the timing performance of the EMC was considered an important issue. A good time resolution (better than 1 ns) is required for the suppression of random coincidences. The timing performance of scintillation detectors is mainly limited by variations of the signal shape and the signal-to-noise ratio. The variation of the signal shape is caused by the scintillation mechanism in the detector crystals [57, 58, 59].

Traditionally, a constant-fraction time pick-off is performed by producing a trigger at the zero-crossing level of a bipolar pulse [57], which is created by subtracting an attenuated copy of the input pulse from a delayed copy of the same pulse [57]. In our signal processing procedure the CFT algorithm is implemented digitally after the MWD operation:

$$CFT[n] = MWD[n] - k \cdot MWD[n + d]$$  \hspace{1cm} (5.12)

where $n$ is the sample number, $k$ is an attenuation coefficient (giving the “constant fraction”), and $d$ is a delay. In our measurements, the $k$ value was set to ~40% of the original pulse amplitude and the delay was set equal to the signal rise time. When we digitally transform the unipolar preamplifier signal to the bipolar CFT signal, the bipolar signal crosses the time axis and this zero-crossing is considered a well-defined time-stamp.
Figure 5.13 shows the process to obtain the CFT signal by applying digital signal processing techniques. The signal is analyzed by a linear interpolation to determine the zero-crossing time. This time stamp defines the arrival time of the pulse (or the event).

![Figure 5.13: The signal processing sequence to obtain the CFT signal and the time stamp. Top: the raw LNP preamplifier signal, middle: the resulting MWD (blue histogram) and smoothed MWD (red histogram) pulses; bottom: the CFT signal.](image)