Front-End Electronics and Feature-Extraction Algorithm for the PANDA Electromagnetic Calorimeter

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Abstract. The PANDA collaboration at FAIR, Germany, will employ antiproton annihilations to investigate yet undiscovered charm-mesons and glueballs aiming to unravel the origin of hadronic masses. A multi-purpose detector for tracking, calorimetry and particle identification is presently being developed to run at high luminosities providing up to $2 \cdot 10^7$ interactions/s. A trigger-less data-acquisition system will be employed with sub-detectors continuously providing data from incoming physics events. This paper describes readout electronics and the treatment of the digitised preamplifier signal for the Electromagnetic Calorimeter. The use of a Sampling ADC in the readout allows to achieve the design goals, namely a large dynamic range from 1 MeV to 10 GeV, a count-rate dependent low trigger threshold of about 1 - 3 MeV, and a time resolution better than 1 ns.

1. Introduction

1.1. PANDA Electromagnetic Calorimeter

PANDA is a general purpose hadron physics detector planned to be operated at the future Facility for Antiproton and Ion Research (FAIR) at Darmstadt, Germany. It will use cooled antiproton beams with a momentum between 1.5 GeV/c and 15 GeV/c and a momentum resolution up to $\Delta p/p=10^{-5}$. With hydrogen and various internal targets a peak luminosity of $2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$ can be reached, allowing for up to $2 \cdot 10^7$ interactions/s. This, together with the high momentum resolution, allows to measure masses and widths of hadronic resonances with an accuracy 10 to 100 times better than achieved in any $e^+e^-$-collider experiment. In addition states of all quantum numbers can be directly formed in antiproton-proton annihilations.

A sketch of the PANDA spectrometer is shown in figure 1. To obtain a good momentum resolution the detector is split into a target spectrometer at large angles based on a 2 T superconducting solenoid magnet surrounding the interaction point and a 2 Tm forward spectrometer based on a dipole magnet for small angle tracks. In both spectrometer parts tracking, charged particle identification, electromagnetic calorimetry and muon identification are available to allow to detect the complete spectrum of final states relevant for the PANDA physics objectives.

The experiment is focusing on hadron spectroscopy, in particular aiming to search for exotic states in the charmonium mass region, on the interaction of charmed hadrons with the...
nuclear medium, on double-hypernuclei to investigate the nuclear potential and hyperon-hyperon interactions as well as on electromagnetic processes to study various aspects of nucleon structure. These physics goals define the requirements for the PANDA-detector. For precision spectroscopy of charmonium states and exotic hadrons in the charmonium region it is extremely important to measure low-energy photons as final states with many photons can occur. Therefore, a low photon threshold of about 10 MeV is a central requirement for the ElectroMagnetic Calorimeter (EMC). This requires a threshold for individual crystals of about 3 MeV and correspondingly low noise levels of 1 MeV. Neutral decays of charmed mesons require the detection of a maximum photon energy deposition of 12 GeV per crystal at the given maximum beam energy. These requirements dictate the dynamic range for the readout electronics.

The PANDA EMC [1] will consist of PbWO$_4$ (PWO-II) crystals [2] arranged in the cylindrical barrel EMC with 11360 crystals, the forward endcap EMC with 3600 crystals and the backward endcap EMC with 592 crystals. In order to gain maximum light output from the PWO-II crystals, the calorimeter volume will be cooled to -25°C. The EMC will be placed inside the 2 T solenoid magnet of the target spectrometer. Therefore, the Large Area Avalanche PhotoDiodes (LAAPD) and Vacuum Photo Triodes/Tetrodes (VPT) were chosen as photosensors. The LAAPD will be employed for the backward endcap and the barrel parts of the EMC where the single-crystal hit-rate is expected to be in the range of 10 to 100 kHz. Two rectangular LAAPD with a sensitive area of $14 \times 6.8 \, \text{mm}^2$ each will be used to read each EMC crystal. For the forward endcap the VPT will be used because of higher expected single-crystal hit rates up to 500 kHz.

The gain of LAAPDs and VPTs is not sufficient to directly read out the output signals. Therefore, special low-power and low-noise preamplifiers were developed. The discrete component preamplifier (LNP) [3] will be used for the VPT readout, and the ASIC APFEL II [4] for the LAAPD readout. The ASIC has a built-in two-stage shaper and provides two output signals with high and low gains. The discrete preamplifier is a one-range resistor-reset type with decay constant of 25 $\mu$s. To achieve the best performance the preamplifiers will be placed near the photo-sensors and, therefore, will be kept at the same temperature as the EMC crystals, namely at -25°C.

For optimal conditions of event selection the PANDA experiment uses a triggerless data acquisition system. This requires that all sub-detectors have to provide all single-hit event information. The acquired data are sorted according to the time-stamps by the data acquisition...
1.2. PANDA-EMC prototype setup

Measurements with the prototype Proto60 [1] were carried out to estimate the expected performance of the PANDA EMC. The Proto60 comprises 60 PWO-II crystals cooled to $-25^\circ$C and read out by one square LAAPD with a sensitive area of 1 cm$^2$, coupled to a LNP preamplifier. Measurements were done using tagged photons at the MAMI-C electron accelerator facility at Mainz, Germany. Fifteen tagger-defined energies in the range of 124 MeV – 1.4 GeV were selected. A matrix of $3 \times 3$ crystals was read out by the 100 MHz 16 bit SIS3302 SADC [6] operated in different runs at 100 MHz and at 50 MHz. The beam-spot diameter of the photon beam was about 1 mm, pointing to the centre of the middle crystal. The data acquisition was triggered by the external signal from the electron-tagger detectors. For each event 10 $\mu$s long traces were stored for all 9 channels. The obtained data were analysed offline, emulating the on-line feature-extraction algorithm. After optimisation the algorithm was implemented in VHDL for the SIS3302 SADC [6] enabling on-line data analysis for the future test experiments with the Proto60. The energy calibration of the individual channels of Proto60 was obtained from cosmic-ray data.

2. Performance of the EMC prototype

2.1. Noise level and energy resolution

To extract the information on the energy deposition from the digitised preamplifier signals the Moving Window Deoconvolution (MWD) [7] and Moving Average (MA) filters are used, see ref. [5] for more details. The noise level which determines the triggering threshold depends on the length of the MA filter (see figure 2). The length of the MA filter defines as well the
Figure 4. Measured time resolution RMS (black points) as a function of the energy deposition in the PWO-II crystal. The red solid line corresponds to the fitted curve with energy E given in GeV.

total width of the resulting pulse after the digital shaping and, therefore, the pile-up probability. Taking into account the single-crystal hit-rate between 100 and 500 kHz expected for the forward EMC-endcap the maximum tolerated pulse-length is about 100 ns. Therefore, the maximum MA-filter length is about 80 ns. As can be seen from figure 2, the achieved noise level is about 1 MeV in this case. The expected hit-rate for the barrel and backward endcap of the EMC is much lower and, therefore, longer shaping times can be used providing even better noise performance. To cover the required dynamic range up to 12 GeV, the resolution of the SADC should be 14 bits.

The cluster energy resolution measured with a $3 \times 3$ PWO-II crystal sub-matrix for the tagged photons is shown in figure 3. The measured energy resolution was fitted using the function $\sigma/E = A_0 + A_1/\sqrt{E/\text{GeV}}$ and the parameters $A_0 = 0.3\%$ and $A_1 = 2.05\%$ were found. In the Technical Design Report for the PANDA EMC [1] the limits $A_0 \leq 1\%$ and $A_1 \leq 2\%$ are required. The energy resolution of the EMC prototype almost fulfills these requirements with a marginally bigger stochastic term $A_1$. To allow for more than nine crystals per cluster would provide a better electromagnetic shower collection and, therefore, improve the energy resolution. As mentioned above in sect. 1.1, in the final configuration of the EMC each PWO-II crystal will be equipped with 2 LAAPD covering about 2 cm$^2$ of the crystal end-face. This larger coverage will lead to an improved photo-electron statistics and, according to test results, to an additional improvement of the resolution by almost a factor $\sqrt{2}$. Two independent readout channels per crystal will also increase the redundancy of the EMC and will allow to discriminate events contaminated by the nuclear-counter effect (i.e. detection of charged particles which penetrate the LAAPD).

2.2. Time resolution

To determine the precise time-stamp of signal pulses, the digital implementation of the constant-fraction discrimination is applied [5]. This method allows to achieve a timing precision much higher than the SADC sampling rate. To measure the time-resolution of the EMC-prototype, a special measurement was carried out. The tagged-photon beam was directed between two PWO-II crystals. During the data-analysis only events with about the same ($\pm 10\%$) energy deposition in both crystals were selected. The time-resolution RMS for the single channel was deduced from the distribution of the time-difference between two crystals and is shown in figure 4 as a function of the energy deposition in the PWO-II crystal. For the energy deposition above 80 MeV the time resolution reaches below the level of 1 ns and improves to about 0.5 ns at 300 MeV. The achieved timing precision is much higher than the SADC sampling rate (50 MHz, see sect. 1.2) and is sufficient to relate hits in the PANDA-EMC to the primary-interaction events as well as suppress random coincidence background.

A sampling rate of about 40-50 MHz is optimal for the readout of the LNP preamplifier.
signal. The usage of higher sampling rates does not improve the timing performance of the EMC and at the rate of about 25 MHz the time-resolution will worsen by about a factor of 2.

2.3. Performance at high rates

As mentioned above in the sect. 1.1 and 2.1, the forward endcap of the PANDA-EMC will operate at high single-hit rates, up to 500 kHz. To avoid pile-up of different events it is extremely important to keep the hit-response of the single-crystal detector as short as possible. The pulse-shape of the LNP preamplifier, used in the forward endcap, is shown in figure 5. The rise time of the pulse is about 100 ns and the fall time is 25 \( \mu \)s. The MWD digital-filter differentiates the incoming pulse and compensates for the exponential discharge of the integrating capacitor in the preamplifier. Therefore, the resulting pulse has the required width defined by the differentiating time-constant of the MWD filter. As can be seen in figure 5, the MWD filter does not distort the rising edge of the incoming pulse and the trailing edge repeats the shape of the rising one. For the LNP preamplifier this leads to the appearance of the exponential tail after the pulse, effectively increasing the total width of the resulting pulse by 100 ns. Therefore, the minimum achievable total pulse-width is about 300 ns. In addition, the application of the MWD filter with the differentiating time-constant shorter than the rising edge leads to a decreased amplitude of the resulting pulse while keeping the same noise level. This effectively increases the threshold for the hit-detection.

It was found that the resulting tail of the LNP-preamplifier pulse, shaped by the MWD filter, has an exponential behaviour. Therefore, such tail can be compensated applying a second MWD filter with the corresponding decay-constant. The resulting LNP-preamplifier pulse after double MWD shaping is shown in figure 5. The double MWD filtering allows to obtain much shorter pulses and recover its original amplitude for short differentiating time-constants without increasing the noise level. Figure 6 shows the recovery of the pulse amplitude after the double MWD filtering as a function of the differentiation time-constant of the first MWD filter. Only for the very short differentiation time-constant, below 80 ns, the pulse amplitude can not be completely recovered even though providing a much higher amplitude than the single MWD filtering. Such signal recovery technique allows to effectively achieve a low triggering threshold while reducing the pulse width.

The usage of the double MWD filtering does not influence the resulting energy resolution of the detector. As can be seen in figure 7 the cluster energy resolution for \( \gamma \)-rays is the same for the single and double MWD filtering. For the forward endcap of the PANDA-EMC 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.
3. Conclusions
The measurements performed with the EMC prototype Proto60 using SADC readout demonstrated the performance close to the design goals of the PANDA-EMC. Namely it is possible to obtain a large dynamic range from 1 MeV to 10 GeV, a low trigger threshold of about 1 – 3 MeV, depending on the single detector hit rate, a time resolution better than 1 ns for an energy deposition above 80 MeV. The SADC sampling rate of about 40-50 MHz is sufficient to extract all the information from the LNP-preamplifier signals without loosing time and energy resolution. Such a low sampling rate and correspondingly moderate power consumption will allow to integrate the SADC into the front-end electronics at the calorimeter.

The digital filtering, namely double MWD shaping, allows to reduce the time span for the single-hit response of the EMC detector to about 160 ns. This reduces the hit pile-up probability.

The results presented in this paper are based on the off-line analysis of recorded signal traces. The used feature-extraction algorithm is implemented in VHDL for the FPGA logic of the SADC. Therefore, future tests of the PANDA-EMC prototypes will be performed under even more realistic conditions.

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