Verification of a novel calorimeter concept for studies of charmonium states
Guliyev, Elmaddin

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Summary

The Standard Model of particle physics has been very successful in identifying three generations of quarks, leptons, and various bosons as the fundamental and elementary building blocks of matter. It remains a challenging puzzle to understand the underlying mechanisms that are responsible for the properties of nucleons, protons and neutrons, which are the building blocks of atomic nuclei. Hadrons containing charm quarks are the most promising laboratories that may reveal the secrets of the strong interaction on the long-distance scale which is relevant for the structure of hadrons. Precision measurements of mass, width and decay branches of all charmonium states will provide information on the quark-confining potential and its spin dependence (see Figure 1, left panel). The charmonium states above the $D\bar{D}$ thresholds are poorly explored.

Calculations using the discretized strong interaction (QCD) on a space-time lattice (LQCD) predict yet unobserved composite particles like glueballs (see Figure 1, right panel). Light glueballs are experimentally hard to identify since they may mix with ordinary mesons. Therefore, heavy glueballs with exotic quantum numbers would be narrower and easier to detect.

In order to study the strong interaction in the non-perturbative regime of QCD, the PANDA experiment for proton-antiproton annihilations has been designed. With anti-proton beams in the momentum range 1.5 - 15 GeV/c, provided by FAIR Darmstadt, states with exotic quantum numbers, as predicted by LQCD, can be excited. PANDA aims to study hadrons containing a charm quark or consisting of a charm ($c$) and anti-charm ($\bar{c}$) quark. The physics program of the PANDA experiment focuses on charmonium spectroscopy and the search for hybrid states and glueballs (see Figure 2). Moreover, a large variety of other
physics topics such as the study of hypernuclei, in particular those with two \( \Lambda \) hyperons, and measurements of the timelike form factor of the proton [6] will be addressed.

![Figure 2: Mass range of hadrons that will be accessible by the PANDA experiment. The upper scale indicates the corresponding antiproton momenta.](image)

The broad physics program requires a compact and multi-purpose detector system with a high-resolution Electromagnetic Calorimeter (EMC). This thesis focuses on optimizing the EMC for most sensitive and high-rate studies. High precision studies of rare processes require a fast, complex and safe selection of promising events. Thus, the readout electronics should be able to provide high-level triggering information, like the invariant mass of neutral mesons or decay vertices. The first and most important stages of such readout electronics for the PANDA EMC have been developed, tested and evaluated in the context of this thesis.

**PANDA Detector**

The PANDA detector (Figure 3) will be installed at the High-Energy Storage Ring (HESR) at FAIR to detect the various types of particles after the annihilation of anti-protons. The detector can operate at high annihilation rates up to \( 2 \cdot 10^7 \) annihilation/s, will have a good particle identification, high momentum resolution, excellent vertex reconstruction and high-resolution calorimetry. Moreover, a new approach for event selection will be employed in order to increase efficiency and quality of data collection. In this approach all detector channels will be self triggering entities, providing all information to the data acquisition system. This information will be used for the selection of events based on the physics properties of particles, such as reconstructed invariant mass or a detected secondary vertex. This approach is named a trigger-less data acquisition [28].
Calorimetry for PANDA detector

A crucial component of the PANDA detector is the Electromagnetic Calorimeter (EMC). The EMC will detect high-energy electrons, positrons and photons in the final state with high time and energy resolutions. The EMC was designed to achieve an almost $4\pi$ coverage in the target spectrometer (see Figure 3).

The calorimeter will be able to detect electromagnetic particles in a wide dynamic energy range, from 10 MeV up to 10 GeV. This range is dictated by the physics program of the PANDA experiment. For high annihilation rate a fast-response calorimetry is required. On the other hand, precision spectroscopy requires high granularity of the calorimeter. For this purpose the PbWO$_4$ (PWO) material has been chosen to construct the calorimeter. The placement of the detector in a high 2 T magnetic field prevents the use of photomultipliers as a photo sensors. Therefore, large-area avalanche photo diodes will be used. The EMC will be operated at -25 °C temperature in order to increase the light yield of PWO crystals and to improve the EMC performance.

![Figure 3](image)

**Figure 3**: The Target Spectrometer (left part) and the Forward Spectrometer (right part) of the PANDA detector. The various sub-detector components are indicated.

Feature-extraction algorithm

In order to fulfill the requirements for a trigger-less data acquisition system, the preamplifier signals will be continuously digitized by Sampling ADCs and the resulting data will be processed on-line by the feature-extraction algorithm in FPGA. For the hit-detection and the determination of energy and arrival time of the incoming events the feature-extraction algorithm has been developed in this work. The algorithm consists of different functions, such as Moving-Window Deconvolution (MWD) for pulse filtering, Moving Average (MA) for noise reduction and Constant Fraction Timing (CFT) for determination of the time stamp. The maximum of the MWD filtered signal provides the energy information; the zero-crossing of the bipolar constant fraction timing signal provides the time-stamp information.

The developed algorithm was verified by experiments with EMC prototypes [56]. The obtained results indicate that the EMC equipped with such electronics will fulfill the requirements for the physics program of the PANDA experiment. The feature-extraction...
algorithm was applied for off-line data taken with Proto60, the prototype of the PANDA EMC. The experiment was performed with high-energy photons impinging on an array of 60 PWO crystals. The resulting energy and time resolutions are satisfying and are shown in Figure 4. The obtained energy resolution is 2.4(1)% for 1 GeV photon energy and the time resolution is less than 1.0(1) ns for an energy deposition above 100 MeV.

![Graph](image1)

**Figure 4:** Top: The energy resolution for a $3 \times 3$ array of PWO crystals as a function of the photon energy. Bottom: The time resolution for different energy depositions.

In addition, the developed digital shaping allows to shorten the hit response of the detector and, therefore, to reduce the pile-up probability.

**Performance test of the on-line feature-extraction**

The developed feature-extraction algorithm was implemented in VHDL, the language used for FPGA programming. The test of the FPGA implementation for the on-line data analysis was done with an LED light pulser and for cosmic-muon energy depositions using a single-crystal test setup. The resulting values of energy and time resolutions for the on-line and off-line data analysis were compared. In both cases the analysis parameters, such as differentiation and integration for the digital filters, delay and fraction for CFT, were kept the same. The obtained correlation between the resulting values from off-line and on-line data processing was 99.9% (see Figure 5). The time resolution of 3.16(3) ns is measured using cosmic muons, which corresponds to 20 MeV energy deposition in the PWO crystal.
and this result compares well with the resolution of 3.15(1) ns obtained by the software (off-line) analysis.

![Figure 5: The comparison of the energy resolution $\sigma/\mu$ (left) and timing performance $\Delta t_{\text{mean}}$ (right) for the on-line and off-line (software) pulse processing. The correlation coefficient in both cases is 99.9%.](image)

**Evaluation of PANDA EMC performance**

The rich PANDA physics program aims particularly at precise hadron spectroscopy. The width of the reconstructed invariant mass of narrow resonances plays an important role for the interpretation of such states. To investigate how strong the influence of the readout electronics is on the performance of the detector, Monte Carlo simulations were performed for the $h_c$ charmonium state. To validate the simulations, the response of a $3 \times 3$ crystal array to a single photon with 200 MeV was investigated. The simulation results overlap rather well the experimental results obtained with the Proto60 setup.

After validating the simulation model, the $h_c$ charmonium state was studied for different readout electronics noise, single crystal threshold and cluster threshold values. As an example, in Figure 6 the analysed width of the $h_c$ charmonium state is given for different cluster thresholds. The width of the $h_c$ charmonium state is getting larger at higher cluster thresholds. Additionally, we observe that the width is getting larger due to increasing noise in the readout electronics.

![Figure 6: The width of the $h_c$ charmonium state for different cluster thresholds.](image)
The simulation study of the performance of the PANDA EMC has shown that the EMC has to have the best performance in terms of noise level and high-rate capability, in order to be able to study narrow resonances. The methods developed in this thesis thus lead to optimized performance of the detector system. They can also be applied in various other experimental situations where high rate capabilities are required.