Performance of the prototype of the electromagnetic calorimeter for PANDA


Abstract
The PANDA collaboration at FAIR, Germany, will employ antiproton annihilations to investigate yet undiscovered charm-meson states and glueballs. The aim is to study QCD phenomena in the non-perturbative regime and 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 $2 \times 10^7$ interactions/s. One of the crucial components of the PANDA spectrometer is the Electromagnetic Calorimeter, composed of cooled PbWO$_4$ crystals. This paper describes construction and performance of a fully functioning prototype of this calorimeter. The performance was determined from measurements exploiting cosmic muons and high-energy tagged photons from the MAMI-C electron accelerator. The response measurements were carried out using sampling ADCs and, for comparison, charge-integrating ADCs. The achieved results validate the usage of sampling ADCs with a moderate sampling frequency, provide the energy resolution as foreseen in the Technical Design Report of the full calorimeter, and secure event correlation by achieving a good timing resolution through digital analysis of the sampled signals.

Keywords: Electromagnetic calorimeter, avalanche photo-diode, low-noise low-power preamplifier, sampling ADC readout, digital filtering, noise performance, rate performance, energy resolution, time resolution

1. Introduction
PANDA is a general purpose hadron physics detector planned to be operated at the future Facility for Antiproton and Ion Research (FAIR) [1] at Darmstadt, Germany. PANDA experiments will exploit cooled antiproton beams with a momentum between 1.5 GeV/c and 15 GeV/c and a momentum resolution up to $\Delta p/p = 3 - 4 \times 10^{-5}$. With hydrogen and various internal targets a peak luminosity of $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ can be reached, allowing for up to $2 \times 10^7$ 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 produced in antiproton-proton annihilations.

A sketch of the PANDA spectrometer is shown in figure 1. In order to accommodate the expected particle density and to obtain sufficient particle separation and suitable momentum resolution, the detector is split into a target spectrometer, located inside a 2 T superconducting solenoid magnet surrounding the interaction point, and a forward spectrometer based on a 2 Tm dipole magnet for small-angle tracks. In both spectrometer parts tracking, charged particle identification, electromagnetic calorimetry and muon identification are available to allow detecting complete 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-hypersnuclei 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 charged mesons require the detection of a maximum photon energy deposition up to about 12 GeV per crystal at the given maximum beam energy. These requirements dictate the dynamic range for the readout electronics.

2. The Electromagnetic Calorimeter of PANDA

The PANDA EMC [2] will consist of PbWO₄ (PWO-II) crystals [3] (see sect. 3.3) arranged in the cylindrical barrel EMC (11360 crystals), the forward endcap EMC (3856 crystals), and the backward endcap EMC (ca. 600 crystals). In order to maximize the light output from the PWO-II crystals, the calorimeter volume will be cooled to -25°C (the EMC operating temperature), which provides an increase of scintillation light by approximately a factor 4 [4]. The EMC will be placed inside the 2 T solenoid magnet of the target spectrometer. Therefore, Large Area Avalanche Photo Diodes (LAAPD) [5] and Vacuum Photo Triodes/Tetrodes (VPT) [6] were chosen as photo sensors. The LAAPD will be employed for the backward endcap and the barrel 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 × 6.8) mm² each will be used to detect light from the individual EMC crystals. For the forward endcap the VPT will be employed which are expected to better cope with the higher expected single-crystal hit rates up to 500 kHz.

The intrinsic gain of LAAPDs and VPTs is not sufficient for noise-free signal transmission and digitization of the output signals. Therefore, custom-designed low-power low-noise preamplifiers were developed. The discrete component preamplifier (LNP) [7] will be used for the VPT readout, and the ASIC APFEL II [8] for the LAAPD readout. The ASIC has a built-in two-stage shaper and provides two output signals with high and low gains. The LNP is a one-range resistor-reset type preamplifier with decay constant of 25 μs. To achieve the best performance, the preamplifiers will be placed near the photo sensors and, therefore, will be kept at the EMC operating temperature.

For optimal conditions of event selection the PANDA experiment will employ a so-called trigger-less data acquisition system, i.e. no hardware trigger selection is applied. The decision on the event selection will be based on high-level information like e.g. the invariant mass of reconstructed particles or the presence of a secondary vertex [5]. This approach requires that all sub-detectors have to provide the complete single-hit event information. The acquired data are sorted according to the time-stamps by the data acquisition (DAQ) and the decision on the event selection is made based on the complete information about the primary interaction of the recorded event. To fulfill the requirement of the DAQ, the EMC preamplifier signals are continuously digitized by sampling ADCs (SADC) and the data are processed on-line in FPGAs. The digitizer modules are placed in the EMC volume and kept at room temperature. The placement of the SADC system together with the on-line feature-extraction logic in the vicinity of the cold crystals restricts the allowed power consumption of the digitizer unit and, therefore, the complexity of the feature-extraction algorithm. Therefore, a simple and robust algorithm [9] was developed to process data from both the LNP and the ASIC preamplifiers.

3. PROTO60 – the PANDA EMC prototype

3.1. Overview

Several test setups using real-size components of the PANDA EMC have been constructed in order to validate the concepts of physics performance, mechanical stability, thermal robustness, and integration into the PANDA solenoid together with other detector components. The most complete setup is the real-size PROTO60, composed of 60 crystals of PWO-II. The setup represents the central part of one slice of a barrel EMC segment, assembled of one particular crystal shape (type-6 crystals, see below) in their realistic positions. The design principle is similar to the final one and is detailed in the Technical Design Report [2], except that the crystals, LAAPDs and preamplifiers are easily accessible for reasons of maintenance or checks as needed for a prototype. These elements are supported on a mechanical structure which includes a cooling system and integrates the electronics feedthroughs and calibration system. Figure 2 illustrates the detector configuration and the components described below.
3.2. **The mechanical structure**

3.2.1. **The crystals and their holding structure**

The basic crystal shape is a truncated pyramid, based on the “flat-pack” configuration used in the CMS calorimeter [10]. In this configuration, the crystals are arranged in pairs with a left and right symmetry. Right-angle corners are introduced to simplify the CAD design and the mechanical manufacturing process, thus reducing machining costs. The dimensions of the crystals are related to the global shape and to the discretization of the calorimeter. The type-6 crystal used in this prototype is 200 mm long, the front and back faces are squares with a side length of 21.3 and 27.2 mm, respectively, and the mass is about 1 kg. The tolerances of all dimensions are 0 to -100 μm, which is in accordance with the capability of the manufacturer [11].

The crystals are wrapped with a 63.5 μm thick reflective foil [12] in order to optimize light collection as well as to reduce optical cross talk. This wrapping material is a non-metallic multilayer polymer. In order to provide a thin air gap between the reflector and the crystal face, the foil must be shaped in a mold heated at 80 °C to sharpen the corners.

In the present design, four crystals are packed as shown in figure 3. A group of two pairs of left and right crystals, wrapped with the ESR reflector foil, is contained in one carbon-fiber alveole in order to avoid any load transfer to the fragile PWO crystal. The crystals are held in place by aluminum inserts in the rear end of the alveole. Epoxy pre-impregnated carbon plain weave fabric is precisely moulded in complex tools to fabricate the alveoles which have an expected wall thickness of 200 μm. Each alveole is epoxy-glued to the aluminum insert which is the interface with the support elements. Figure 4 shows a carbon-fiber alveole assembly with aluminum inserts.

The distance between two crystals in the assembly is determined by the thickness of materials, structure deformation and mechanical tolerances and amounts to 0.68 mm. Figure 5 depicts the contributions to the crystal distances:

- 400 μm, twice the thickness of the carbon-fiber alveole wall;
- 130 μm, twice the thickness of the wrapping material;
- 100 μm, the free space reserved for the alveole deformation;
- 50 μm, the approximate manufacturing tolerance.

3.2.2. **Inserts and integration of the electronics**

In the final design, the aluminum inserts are a major part of the mechanical stability, as they are glued to the alveoles to carry the weight of the crystals and position them precisely in the reserved space. In addition, the aluminum structure integrates the cooling, the electronics and the optical fibers for monitoring the optical properties of PWO-II crystals. Figure 6 shows a detail of the insert assembly which, in the present PROTO60 setup, can still be shifted in position for assembly studies. Some aluminum back plates (see figure 2) link the insert assembly to the support frame, described below, but also to the support plate (see figure 2) which carries the weight of the complete assembly of 6 × 10 crystals.

The preamplifiers of the LNP type were manufactured on a PCB in a group of four (Quad preamplifier), screwed on the inserts inside a slot in the back plate, and connected to four APDs by 25 mm long twisted-pair wires. Several columns of PCB, the so called back-PCB, carry the signal lines and the supply voltage and connect the preamplifiers to an external connection panel. These back-PCBs traverse the walls of the thermal insulation layer, which separates the cold crystal volume from the warm environment, through narrow slots. The crystal volume is flooded with nitrogen gas to avoid vapor condensation. Loss of nitrogen gas is avoided by a vacuum tight assembly. The partially assembled PROTO60 apparatus is shown in figure 7 where the preamplifier boards and the back-PCB are visible.

3.2.3. **Cooling system and support frame**

In order to maintain their optimum performances, the PWO-II crystals and the APDs must be cooled to the EMC operating...
temperature, stabilized with a precision of 0.1 °C. The cooling requires a thermal power of about 80 W. The PROTO60 calorimeter setup is equipped with copper thermal screens cooled with serpentines in which the Syltherm coolant \[13\] flows and recirculates by means of a Julabo chiller. The insulation is achieved with 40 mm of styrene foam covered with a gas-tight plastic skin to avoid ice formation. In front of the calorimeter, a prototype of the vacuum insulation panel is successfully operated while its outside face is well above the dew point avoiding any risk of moisture. The vacuum insulation panel has a sandwich structure composed of 2 skins of aluminium and carbon-fibre, connected by rohacell blocks. The vacuum (about \(2 \times 10^{-2} \text{ mbar}\)) between these skins has an equivalent thermal conduction coefficient lower than 2 mW/mK. This system allows to reduce the total thickness of the insulation to 20 mm instead of 40 mm for the standard insulation. A set of 13 thermocouples measures the temperatures at different locations which are recorded with an Agilent data acquisition. The temperature variations of the inlet coolant, selected crystals, and the air inside the prototype stay within ±0.01 °C, ±0.05 °C, and ±0.6 °C, respectively, and verify the required thermal stability.

All the previous elements are mounted on a support frame which provides a rigid base in case of transport to sites of various test experiments. Specially for such tests, the set-up is fixed on a rotating and translating table, which allows to orient the crystals vertically for cosmic muons passing predominantly through the full length of the crystals, or to orient the crystals horizontally for exposure to accelerator beams.

3.3. PWO-II crystals

Based on R&D work in collaboration with BTCP \[11\] the optimum light yield and radiation hardness of PbWO\(_4\) scintillators can be achieved for crystals simultaneously doped with La- and Y-ions. The improved technology has lead to a reduction of the density of defects compared to PWO material employed in the CMS Electromagnetic Calorimeter (CMS-ECAL) \[14\]. As a consequence, the concentration of La and Y dopants has been reduced in a similar manner below an integral value of 40 ppm. The enhanced radiation hardness due to co-doping was studied before for CMS-ECAL in great detail \[3\]. The composition of the raw material was mixed to maintain the exact elemental ratios during the whole growing process. This requires in addition corrections of losses due to evaporation during multiple crystallizations from the starting melt. Performed studies of various electron centers in the crystal directly by Electron Paramagnetic Resonance technique \[15\] confirmed that only single RE-(WO\(_4\))\(^{3-}\) (RE = La, Y) centers are formed, if the concentration of the dopants stays below 20 ppm for each ion, respectively. The quality has been significantly improved due to co-doping with La- and Y-ions at a significantly reduced total level of <40 ppm. Therefore, full size crystals of 200 mm length and nearly rectangular shape contain at least two times less defects of Frenkel type and deliver on average 18 photoelectrons/MeV, as shown in figure 8, measured at room temperature (RT) using a phototube with bialkali photocathode. In addition, the careful selection of the raw material has strongly reduced those impurities leading to slow decay components in particular when the crystals are cooled. As a result, at room temperature these crystals provide an 80% increase in light yield compared to standard-type crystals which were mass-produced for the CMS-ECAL \[3\]. The kinetics of this enhanced material, named PWO-II, remains fast and allows integrating 97% of the light within a 100 ns wide time gate at room temperature. In the
beginning of 2008, the optimization of the properties was completed and ready for mass production for the PANDA-EMC. The 60 PWO-II crystals comprising the PROTO60 are part of pre-production lots produced at BTCP. Figure 9 shows some of the optically polished crystals of the geometry type "6R/L".

Due to the thermal quenching of the luminescence process at room temperature, cooling of the crystals can effectively increase the light yield. However, the obviously low concentration of deep traps in PWO-II does not distort the scintillation kinetics even down to the EMC operating temperature, when 95% of the light can be collected within less than 300 ns. Besides the increased light yield and fast kinetics all crystals fulfill very stringent limits on the optical transparency and homogeneity along the full crystal length as well as sufficient radiation hardness, which is of minor importance in case of prototype tests. For the crystals of the final calorimeter the radiation induced absorption coefficient at 420 nm wavelength has to remain below a value of 1.1/m after exposure to an integral dose of 30 Gy due to γ-rays from a $^{60}$Co source. The extreme radiation hardness is required due to the strongly reduced recovery processes in the crystals at low operating temperatures [16].

### 3.4. Large-area avalanche photodiodes

Each individual PWO crystal of the PROTO60 is optically coupled to a LAAPD with an active area of $(10 \times 10)$ mm$^2$. While these square devices were employed in the PROTO60 EMC prototype, the rectangular LAAPDs with a sensitive area of $(14 \times 6.8)$ mm$^2$ have been developed for future applications to achieve a larger coverage. The main properties of the square devices (type Hamamatsu S8664-1010SPL) at room temperature are listed in table 1. Since the PWO crystals in PROTO60 will be operated at $T = -25^\circ C$, the main characteristics like dark current $I_d$ and gain $M$ have to be determined as function of the operation temperature.

#### 3.4.1. Gain-Bias characterization

The dependence of the APD gain on the applied bias voltage was measured at three designated temperature values: $T = 15^\circ C$, $T = 5^\circ C$ and $T = 1^\circ C$. Typical results of these measurements are shown in Fig.10. It is obvious that the achieved gain value $M$ at a fixed bias voltage $U_B$ increases whereas the breakdown voltage value $U_{Br}$ decreases with decreasing temperature.

To evaluate the bias voltage corresponding to the gain value envisaged during the PROTO60 operation the so called Miller formula [17] (see equation 1) was fitted to the data samples corresponding to the different temperature values.

\[
M = \frac{1}{1 - \left( \frac{U_B}{U_{Br}} \right)^n}
\]
The parameter $n$ is the concavity index of the avalanche zone and depends on the type and concentration of doping used in this region of the APD. From the fit results the dependence of the bias voltages $U_R$ on the operation temperature was determined for three designated gain values $M$ as shown in Fig. 11.

The observed linear temperature dependence $U_R(T,M = \text{const.})$ allows the extrapolation to the bias voltage which has to be applied to the APD at the EMC operating temperature.

### 3.4.2. Dark current measurement

The dependence of the APD dark current on temperature was measured at the same temperature values mentioned above. The resulting dark current values as function of the APD gain are shown in Fig. 12 and can be described by the equation: $I_d(M, T = \text{const.}) = I_{dS} + M \cdot I_{db}$, including the surface dark current $I_{dS}$ and the bulk contribution $I_{db}$ to the overall dark current of the APD. The APD dark current can be reduced to $\approx 1 \, nA$ for the envisaged gain of $M = 50$ by cooling to the EMC operating temperature.

### 3.5. Low-noise low-power preamplifier

A discrete charge preamplifier, the Low-Noise low-Power charge preamplifier (LNP) has been developed [7] for the LAAPD readout of the PANDA Electromagnetic Calorimeter. The LNP employs a low-noise J-FET transistor and has an excellent noise performance in combination with low power consumption. The preamplifier linearly converts the charge signal from the LAAPD to a positive voltage pulse. The single-ended output of the LNP is designed to drive a 50 $\Omega$ transmission line to the subsequent digitizing electronics. Two different modifications of the LNP can handle detector capacitances in a range from 0 $pF$ to 100 $pF$ and from 50 $pF$ to 500 $pF$, respectively.

#### 3.5.1. Power Consumption

Since the complete calorimeter, including LAAPDs and preamplifiers, will be cooled to low temperatures (-25°C) to increase the light-yield of the PWO-II crystals, the power dissipation of the preamplifier has to be minimized. Low power dissipation necessitates less cooling power and supports achieving a small temperature gradient over the length of the crystals. The LNP has a quiescent power consumption of 45 mW. The power dissipation is dependent on the event rate and the photon energy; figure 13 shows the measured power dissipation on the LNP as function of the count-rate in the worst case of maximum output amplitude. Since the high rates are predominantly occurring at lower energies, a reasonable maximum power consumption of 90 mW can be presumed.

#### 3.5.2. Noise

In order to reach the required low detection threshold of only a few $MeV$, the noise performance of the preamplifier is crucial. The LAAPD, used in the PROTO60 setup, has an active area of $(10 \times 10) \, mm^2$ resulting in a quite high detector capacitance of 270 $pF$ which requires a low noise charge preamplifier. The total output noise is a combination of the preamplifier noise and the noise generated by the dark current flowing through the APD. By cooling the APD to -25°C the dark current is reduced by a factor of about ten with respect to room temperature. Using a low leakage LAAPD at low temperature, the charge preamplifier is the dominating noise source due to the relative high detector capacitance. The noise floor of the LNP, loaded with an input capacitance of 270 $pF$, at the EMC operating temperature has a typical equivalent noise charge (ENC).
of 1250 $e^{-}$ (RMS), see figure 14. This result is obtained with an ORTEC 450 [18] shaping filter/amplifier with a peaking time of 650 ns. When the LAAPD as well as the LNP are cooled to the EMC operating temperature the total output noise corresponds to an ENC of about 1700 $e^{-}$ (RMS), also measured with a peaking time of 650 ns. Investigations of the PWO-II light production [19] yielded 500 photons/MeV at the end face of the cooled (-25°C) PWO-II crystal with the typical cross section of a barrel crystal of 745 mm$^2$. Thus the applied LAAPD measures 67 photons/MeV with a quantum-efficiency of about 70% for the scintillating light of the PWO-II crystals. Since an internal gain $M = 50$ is assumed for the voltage biased LAAPD, a primary photon with the energy of 1 MeV induces an input charge of 375 nC (2345 $e^{-}$) to the preamplifier. Thus an ENC of 1700 $e^{-}$ (RMS) corresponds to an energy noise level of about 725 keV (RMS). Possible radiation damage of the APD would lead to a higher dark current and, therefore, to a higher noise level.

3.5.3. Event rate

To cope with the expected event rates in the barrel EMC of up to 100 kHz per crystal, the LNP has a concerted feedback time constant of 25 $\mu$s. This feedback time constant is a trade-off between noise performance and pile-up probability. For a single pulse (or very low rates) the LNP accepts an input charge of up to 4 pC, limited by the positive supply voltage (+6 V) of the LNP. However, for a continuous event rate of e.g. 100 kHz an input charge of up to 8 pC is allowed. This is because at high continuous event rates the output pulses will swing between the negative (-6 V) and the positive (+6 V) supply voltage. If a 100 kHz event rate is applied abruptly (burst) to the LNP it takes around one second until a continuous input charge of up to 8 pC is allowed. During that transition period, a maximum input charge of 1 pC can be handled. With this charge restriction, the output voltage of the preamplifier stays always in the linear range and is never limited from the power supply voltages, provided the digitizing electronics is able to perform a good base-line correction. The charge sensitivity is 0.5 V/pC and thus the maximum input charge of 4 pC corresponds to a positive output pulse with a peak voltage of 2 V at 50 $\Omega$.

3.5.4. Dynamic range

The maximum expected photon energy deposition per crystal of 12 GeV results in an input charge of 4.5 pC. In principle, the energy range of the LNP spans from the noise floor of 0.725 MeV RMS (with a peaking-time of 650 ns) up to the maximum energy of ca. 11 GeV equivalent to an input charge of 4 pC; this corresponds to a theoretical dynamic range of 15,000. In practice, the typical energy range will start from 1.5 MeV (2 x noise RMS) and end at 11 GeV which corresponds to a dynamic range of 7330.

3.6. Signal readout and digitization

A number of calibration measurements and response tests have been carried out in order to verify the performance of the PROTO60 setup under realistic conditions. First, cosmic muons have been used for the rough energy calibration to adjust discriminator thresholds, to adapt the LAAPD gain to the dynamic range of the amplification and digitization circuits, and to extrapolate the bias voltage of the LAAPD specified at room temperature down to the EMC operating temperature in order to keep the gain at a level below 100. The performance of the detector matrix has been studied using tagged muons for the rough energy calibration to adapt the LAAPD gain to the dynamic range of 7330.

3.6.1. PROTO60 positioning for cosmic muons

The reconstruction of the electromagnetic shower requires a relative as well as an absolute calibration of the individual detector modules which is obtained from the measurement of the energy deposition of cosmic muons. The calibration of the deposited energy is based on the known energy loss of 10.2 MeV/cm for cosmic muons in PbWO$_4$ [20]. The geometrical arrangement of the crystal matrix comprising 6 layers
of 10 tapered crystals each leads to a remaining variation of the path length even if nearly vertical muon tracks are selected by coincidence conditions. The uncertainty on the level below 0.5% MESYTEC is due to the slightly tapered crystal shape as well as to the staggered crystal packing. Only the horizontal symmetry plane of the matrix is parallel to the axis of the photon beam. If the detector is rotated into the horizontal position a mean deposited energy of 24.6 MeV has been assumed for all detector components. This value provides the relative as well as the absolute energy calibration. In order to obtain, besides the pedestal offset, an additional reference point the whole detector can be rotated by 90°. In this case muons can be selected which penetrate only a single crystal but along the full length of 200 mm with negligible variations. Figure 15 shows a typical spectrum obtained after 1 week of data taking. All experimental results shown in the subsequent sections are based on the calibration with horizontal orientation of PROTO60 since the data has been collected online during the response measurements. The detailed comparison of the calibrations for both orientations reveals a small inconsistency, which is not yet fully understood. It could be a thermal effect or the difference in light collection. The implemented crystals are optically polished on all surfaces and covered with a homogeneous reflector.

3.6.2. PROTO60 setup at the tagged-photon beam

The reported test experiments were performed with quasi-monoenergetic photons delivered by the recently upgraded tagged photon facility at the electron accelerator MAMI-C at Mainz (Germany) exploiting the tagging of bremsstrahlung produced by a monoenergetic electron beam up to 1.5 GeV energy. After bremsstrahlung emission the momenta of the slowed-down electrons are analyzed by the magnetic spectrometer of the Glasgow-Mainz tagger [21], requiring a time coincidence of the detected bremsstrahlung photon with the corresponding electron identified in the focal plane. Depending on the accelerator beam energy the typical energy width per tagging channel varies between 2.3 MeV and 1.5 MeV, respectively, for an electron beam of 855 MeV. The energy width is close to 4 MeV in case of the maximum energy of 1.5 GeV. In all experiments we have selected up to 16 photon energies to cover the investigated dynamic range. The detector system was mounted on a support structure which could be moved remote controlled in two dimensions perpendicular to the axis of the collimated beam by stepping-motors. The detector was placed typically at a distance of 12.5 m downstream of a collimator system, which was placed at a distance of 2.5 m from the radiator with a set of lead collimators of 1.5 mm diameter. The beam spot projected onto the front surface of the crystal matrix has a circular diameter of ≤ 9 mm. A plastic scintillator paddle in front could be used to identify leptons due to conversion of photons in air or any low-Z material in between. The mechanical setup allowed to direct the photon beam in the center or in between two adjacent crystal elements. Figure 16 illustrates the experimental setup installed at the A2 tagger hall at the MAMI facility. The photon beam is hitting the detector system from the left hand side.

![Figure 16](image_url)

Several test measurements have been performed at different beam energies under identical operating conditions but selecting various photon energies in the energy range up to 1.4 GeV. The crystal matrix was cooled down to the EMC operating temperature.
perature. For the investigation of the optimum energy resolution the collimated photon beam was always directed onto the same central crystals of the matrix (#35). In order to avoid significant pile-up effects, the trigger rate of the central crystal responding to the entire bremsstrahlung spectrum was kept below 10-15 kHz. For studies of position reconstruction the beam was moved to different points of impact or in between two adjacent crystals for timing studies.

3.6.3. Conventional readout electronics and DAQ system

The event selection was determined by a coincidence between the logic OR of the selected tagger channels and the response of the central scintillator module. In addition, simultaneous hits of cosmic muons were recorded under the condition that a muon traversed the complete matrix by triggering a coincidence between the top and bottom crystal layers. In order to monitor the stability of the readout electronics the pedestals of the energy measurement were recorded with a frequency of a few Hz. The individual timing signals of the selected tagging detectors were recorded in a TDC for identification of the photon energies and to reject random coincidences or multiple photon hits. The TDC was started with the event determined by the central crystal and stopped by the delayed tagger signal. The charge signal of the preamplifier was fed into a 16-fold multi-functional NIM module (MESYTEC MSCF-16) [22], which contained a remote controllable multi-channel spectroscopic amplifier (1 μs Gaussian shaping), timing filter amplifier (integration and differentiation set to 50 ns each), and a constant fraction discriminator to serve both the analog and logic circuits. Due to the limitation of the overall dynamic range of the preamplifier and shaper combination, the energy range covered by the ADC was optimized based on the typical lateral distribution of the electromagnetic shower expected. The figures 17 and 18 illustrate for an incident energy of 158.3 MeV and 1.441 GeV, respectively, the deduced response functions of the central crystal, the surrounding 3 x 3 and 5 x 5 sub-arrays as well as the whole PROTO60. Measurements at higher photon energies are planned to study the response at larger distances from the central crystal. The energy depositions measured in the central crystal as well as in the full crystal matrix show a clean linear correlation with the incident energy of cosmic muons, the reconstruction of the total shower energy can be based on an identical absolute energy threshold for each responding detector module. Due to the low noise level a value of 0.75 MeV can be applied as minimum threshold. The figures 17 and 18 illustrate for an incident energy of 158.3 MeV and 1.441 GeV, respectively, the deduced response functions of the central crystal, the surrounding 3 x 3 and 5 x 5 sub-arrays as well as the whole PROTO60. Measurements at higher photon energies are planned to study the response at larger distances from the central crystal. The energy depositions measured in the central crystal as well as in the full crystal matrix show a clean linear correlation with the incident photon energy within the experimental uncertainties. The individual line shapes have been fitted using the so called Novosibirsk function [26]. The fit procedure takes into account the full crystal matrix show a clean linear correlation with the incident photon energy within the experimental uncertainties. The individual line shapes have been fitted using the so called Novosibirsk function [26].

4. PROTO60 performance

As shown in the previous section, the response function of the fixed arrangement of the PROTO60 has been investigated in parallel applying two signal processing and analysis schemes, the conventional readout as a continuation of the long list of exploratory experiments and the SADC readout as it is foreseen in the final PANDA-EMC concept. In the following, the relative and absolute calibration as well as the event selection for the different photon energies are treated in the same way.

4.1. Data analysis based on charge-integrating readout

4.1.1. The energy response - line shapes and resolutions

After the relative and absolute calibration, exploiting the deposited energy of cosmic muons, the reconstruction of the total shower energy can be based on an identical absolute energy threshold for each responding detector module. Due to the low noise level a value of 0.75 MeV can be applied as minimum threshold. The figures 17 and 18 illustrate for an incident energy of 158.3 MeV and 1.441 GeV, respectively, the deduced response functions of the central crystal, the surrounding 3 x 3 and 5 x 5 sub-arrays as well as the whole PROTO60. Measurements at higher photon energies are planned to study the response at larger distances from the central crystal. The energy depositions measured in the central crystal as well as in the full crystal matrix show a clean linear correlation with the incident photon energy within the experimental uncertainties. The individual line shapes have been fitted using the so called Novosibirsk function [26]. The fit procedure takes into account the full lineshape, in particular the low-energy tail due to signal losses, and delivers the peak positions as well as the FWHM. The quoted energy resolution is obtained as $\sigma = \text{FWHM}/2.35$.

![Figure 17: The experimental lineshape of the central crystal, the 3x3- and 5x5-matrices as well as of the whole PROTO60 measured at 158.3 MeV incident photon energy.](image)
Figure 18: The experimental lineshape of the central crystal, the 3x3- and 5x5-matrices as well as of the whole PROTO60 measured at 1.441 GeV incident photon energy.

Figure 19: The energy resolution of the PROTO60 (points) shown as a function of incident photon energy. All detector modules responding above a threshold of 0.75 MeV have been included into the response function.

Figure 20: Measured energy resolution of the PROTO60 shown for restricted matrix sizes and energy threshold of 0.75 MeV.

Figure 21: Energy resolution of the entire PROTO60 array deduced for different settings of the energy threshold.

Figure 22: Energy resolution of the entire PROTO60 array deduced for different positions of the photon beam relative to the centre of a crystal.

Figure 19 summarizes the energy resolutions obtained over the entire energy region of the incident photons; all detector modules responding above the energy threshold of 0.75 MeV have been included. The indicated fit with two parameters confirms a relative energy resolution of 2.4% at 1 GeV photon energy, which is close to the design value for the EMC. The obtained results are strongly dependent on the maximum size of the considered crystal matrix as well as the threshold settings. These effects are illustrated in the figures 20 and 21.

Strongly depending on the energy threshold the mean multiplicity of responding modules reaches a value of 22.5 at the maximum photon energy of 1.44 GeV for the minimum energy threshold of 0.75 MeV. The multiplicity is reduced by a factor of two if the threshold is set to 3 MeV, or even reaches a value of 8 for a threshold of 10 MeV.

In order to estimate the variation of the energy resolution if photons are not impinging on the center of a crystal, figure 22 illustrates the deterioration of the resolution for three different points of impact. Position 1 corresponds as a reference to the central impact. In case of position 2 the center of the photon beam, which has a typical diameter of 8-10 mm, was shifted horizontally 5 mm off center and position 3 is located between two adjacent crystals. The latter case shows the maximum effect leading to a shift of resolution by approximately 1 % due to enhanced shower losses in dead material.
4.1.2. Position reconstruction

The information on the lateral distribution of the electromagnetic shower developed within the PWO matrix can be used to improve the reconstruction of the point of impact of the incident photon. The individual crystals have a diameter close to the Molière radius of PWO (2.2 cm). Supported by the low-energy threshold and the consequently high multiplicity of responding modules the position of the incoming photon has been deduced using the standard procedure employing a logarithmic weighting of the individual detector contribution according to the formula:

\[ W_i = W_0 + \ln \frac{E_i}{E_T} \quad \text{with} \quad E_T = \sum_i E_i \]  

(2)

The values \( E_i \) are the measured energy depositions in crystal \( i \) of the considered crystal matrix. A weighting parameter of \( W_0 = 4.8 \) has been chosen and allows a good reproduction of the point of impact over the entire energy range. The achievable position resolution is strongly dependent on the incident photon energy as shown in figure 23. The shown resolution values are not corrected for the spot size of the impinging photon beam which had a typical diameter of 9 mm on the front surface of the detector. Therefore, the obtained position resolution at the highest energies appears to reflect the dimensions of the photon beam.

\[ \sigma_X = 2.26(5) \, \text{mm} + 2.02(4) \, \text{mm} \sqrt{\frac{E}{\text{GeV}}} \]

\[ W_0 = 4.8 \]

Figure 23: The resolution of the reconstructed position as function of the incident photon energy.

4.1.3. Time response

An estimate of the achievable time resolution, which is in the present case determined by the photosensor and the subsequent readout electronics, was deduced from the relative timing between a PWO detector module and the corresponding tagger plastic scintillator for selecting the photon energy. Since the settings of the Constant Fraction Discriminator could not be optimized by remote control, the timing signals have been corrected for walk in the off-line analysis. The contribution to the time resolution of the plastic scintillator can be neglected. Figure 24 illustrates the good time resolution per detector module, which will allow to determine a well defined time mark for the trigger-less DAQ concept of PANDA. Above an energy deposition of \( \sim 300 \, \text{MeV} \) even sub-ns timing will become possible.

\[ \sigma = 0.20(5) \, \text{ns} + 0.50(5) \, \text{ns} \sqrt{\frac{E}{\text{GeV}}} \]

Figure 24: Time resolution of a single detector module as a function of the deposited energy.

4.2. Data analysis based on SADC readout

As mentioned in section 3.6.4, the 10 \( \mu \)s long traces of 9 SADC channels were stored in case of valid pulse detection in the central crystal. The trace for each crystal was processed using the newly designed feature-extraction algorithm. The algorithm detects pulses in the sampled trace and finally reports the energy and time-stamp information. Subsequently, these reduced data were analyzed to reconstruct the position and energy of the electromagnetic shower and to determine the energy and time resolution.

4.2.1. Feature-extraction algorithm

The feature-extraction algorithm consists of several steps, namely: the pulse shaper, the baseline follower, trigger logic, energy and time readout. As was mentioned in section 3.5, the LNP signal has a long decay constant of \( \tau = 25 \, \mu \text{s} \). To reduce the width of the pulse the Moving Window Deconvolution \[27\] (MWD) is applied as a digital filter to the non-shaped LNP signals (see figure 25). The MWD filter can be described by the following expression:

\[ MWD_M(n) = x(n) - x(n - M) + \frac{\ln 2}{\tau} \sum_{i=n-M}^{n-1} x(i), \]  

(3)

where \( M \) is a parameter which defines the output pulse length and \( x(n) \) is the n-th input sample. The result of the MWD filter is shown in figure 25. The MWD filter does not distort the leading edge of the pulse. This is essential for the time stamping of the event. The length of the MWD filter \( M \) should be larger than the signal rise time, otherwise the amplitude of the resulting pulse will be reduced. According to figure 25, showing the pulse measured with the EMC prototype, the minimum length of the MWD filter should be above 200 ns. The reduction of the pulse height decreases the energy resolution as shown in figure 26. For low MWD-length values the energy resolution improves with increasing MWD length. However, above
200 ns the energy resolution stays roughly constant with slight deviations at larger $M$ values due to the influence of noise.

Following the MWD filter, the base-line is subtracted for the further processing of the signal. To reduce the noise level, the Moving Average (MA) smoothing filter is applied:

$$MA_L(n) = \sum_{i=n-L}^{n} x(i),$$

(4)

where $L$ is the smoothing length. The energy information is obtained by measuring the amplitude of the MA signal. The effect of the smoothing procedure on noise level and energy resolution is shown in figure 26. The MA filter decreases the noise level but does not influence the energy resolution. In case the MA smoothing is applied, the length of the MWD filter should be increased and should be larger than the sum of the pulse rise time and the length of the MA filter. Figure 26 shows the dependence of the cluster energy resolution on the MA smoothing length for an MWD filter length of 400 ns. In this case the optimal MA smoothing length is about 80 ns; resulting in a noise level of about 700 keV. An even lower noise level may be achieved by increasing the lengths of both the MWD and the MA filters. However, in such case, the resulting pulse has a large width. This effect increases the pile-up probability at high rates. Therefore, for the high-rate case, a shorter smoothing length is preferable to provide the best energy resolution and to reduce the pile-up probability. In case a low trigger threshold is required, the smoothing length can be increased up to $L = 400$ ns to achieve a noise level of about 300 keV.

To determine the precise time-stamp of signal pulses, the digital implementation of the Constant-Fraction Timing (CFT) was applied. The CFT signal, shown in figure 25, is obtained from the MWD signal by applying the following filter:

$$CFT_{D,R}(n) = MWD(n - D) - R \cdot MWD(n),$$

(5)

where $D$ is the delay defined by the rise time of the signal. A value $D = 100$ ns was applied. The $R$ parameter defines the pulse-height fraction, which is relevant to obtain the best possible time-stamp. The optimal value $R = 0.4$ was found. The linear interpolation for two points (one below and one above the zero level) is employed to determine the zero-crossing point resulting in a time reference with a precision much better than the sampling interval.

4.2.2. Data-analysis procedure

In order to extract information on the detected signals from the recorded traces the feature-extraction algorithm with the
following parameters was applied: the MWD and MA filter lengths were set to $M = 400 \text{ ns}$ and $L = 80 \text{ ns}$, respectively, yielding a trigger threshold, defined as three times the RMS noise level, of about $2 \text{ MeV}$. Within one event only the hits within the $200 \text{ ns}$ wide time-coincidence window were used for the electromagnetic shower reconstruction. The position of the time-coincidence window relative to the beginning of the trace was defined by the hardware trigger logic of the DAQ. The energy calibration of the individual channels of the PROTO60 was obtained from the cosmic-muon measurement.

The base-line follower of the feature-extraction algorithm is designed for the on-line analysis of a continuous stream of data as expected in the PANDA experiment. The preamplifier signal is continuously digitized and subsequently analysed in a Field Programmable Gate Array (FPGA). The on-line analysis scheme is mandatory to realise an efficient and simple readout concept for the large amount of data, about $170 \text{ MB/s}$, produced by the SADC for nine detector channels. Therefore, as mentioned in section 3.6.4, for the test-beam data only short traces, about $10 \mu\text{s}$ long, were stored for each DAQ trigger and thus the obtained data stream was not continuous. Each trace was analysed by assuming a constant base-line. This approach effectively increases the noise level, as each variation of the base-line might constructively interfere with the electronic noise.

Alternatively, the base-line follower should be initialised for each trace independently. In this case, we assume that the signal at the beginning of each trace is not influenced by the background pulses, which might occur just before the DAQ trigger. The proper base-line initialisation might take some ten $\mu\text{s}$. This is not a problem for the envisaged on-line data-analysis, as the initialisation will take place only once, i.e. during the power-up cycle of the SADC module. However, in the case of PROTO60 measurements, the base-line for the current trace will not be determined properly for channels with high signal rates. This effect is shown in figure 27 for the central crystal of the electromagnetic shower. From the cosmic-muon measurements or from channels with low counting rate, see figure 27, it was observed that the base-line of the MWD signal is very stable. A standard deviation of only about $0.6 \text{ MeV}$ was measured for the distribution of base-line values over all the data-taking period. Therefore, constant values of the base-line are justified for the data-analysis of the test-beam data. In the PANDA experiment, the digitized signals will be processed on-line and the properly applied base-line follower will allow to improve the resulting energy resolution and to reduce the pulse-detection threshold.

### 4.2.3. Energy resolution

The cluster-energy resolution, determined in a way described in section 4.1.1, measured for tagged photons with a $3\times3$ PWO-II crystal matrix in two different runs is shown in figure 28. The photon-energy range for the first run was $61.5–685.6 \text{ MeV}$, and $124.6–1441.1 \text{ MeV}$ for the second one. All experimental conditions for both runs were kept the same but in the first run there was a slight shift of the beam position relative to the center of the crystal. This misalignment might explain the slight discrepancy of the cluster-energy resolution in the overlapping region. The measured energy resolution was fitted using the function

$$
\sigma/E = A_0 + A_1/\sqrt{E/\text{GeV}}
$$

and the parameters $A_0 = 1.02(5)%$ and $A_1 = 1.67(3)%$ were found yielding an energy resolution of about $2.7%$ at $1 \text{ GeV}$. These values should be compared with the ones obtained using the charge-integrating readout for 9 crystals, see figure 20. As can be seen, the SADC readout performs better than the conventional readout electronics at the lower energies. In the Technical Design Report for the PANDA EMC [2] the limits $A_0 \leq 1\%$ and $A_1 \leq 2\%$ are expected. The energy resolution of the EMC prototype fulfills these requirements. Furthermore, as can be seen from figure 20, allowing for more than nine crystals per cluster would provide a better electromagnetic shower collection and, therefore, improve the energy resolution.

The cluster energy resolution for different single-crystal thresholds measured for tagged photons with a $3\times3$ PWO-II
crystal matrix is shown in figure 29. The measured energy resolution shows a strong dependence on the trigger threshold, comparable with the effect demonstrated in figure 21 for data measured with charge-integrating electronics. A lower threshold yields a more complete shower reconstruction and, therefore, a better energy resolution. In the case of a 3x3 crystal matrix this effect is obvious mainly for low photon energies as for higher energies the energy deposition in the surrounding crystals is much higher than the applied threshold.

In order to determine the optimal SADC sampling rate the data of the first run, measured with 100 MHz sampling frequency, was analysed in different ways employing software re-sampling in order to emulate 50 MHz and 25 MHz SADC sampling rates. The effect of a reduced sampling frequency on the cluster-energy resolution is shown in figure 30. A slight deterioration of the energy resolution at lower energies is observed only at 25 MHz sampling rate. Thus, the 50 MHz sampling frequency is high enough to achieve the best possible energy resolution.

4.2.4. Time resolution

To determine the time-resolution of the EMC prototype detector, a special measurement was carried out. The SADC sampling frequency was set to 50 MHz. The tagged-photon beam was directed between two PWO-II crystals. During the data analysis only events with about the same (±10%) energy deposition in both crystals were selected. The RMS time resolution for a single channel was deduced from the distribution of the time differences between two crystals and is shown in figure 31 as a function of the energy deposition. For an 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 better than the SADC sampling interval and is sufficient to correlate events, relate hits in the PANDA EMC to the primary interaction, and efficiently suppress random coincidence background.

To investigate an effect of the SADC sampling rate on the achieved time resolution the data obtained at 50 MHz SADC sampling rate was reduced to 25 MHz sampling frequency using software re-sampling. The measured time resolution for such an analysis is shown in figure 31 as well. The reduction of the SADC sampling rate slightly deteriorates the achieved time resolution. This can be understood as the worsening of the description of the CFT signal (see figure 25) by the linear interpolation between measured points. Therefore, the CFT timing becomes less precise. This interpolation error can be reduced by increasing the sampling frequency. However, as can be seen from figure 31, doubling of the sampling frequency only slightly improves the time resolution. Thus, the achieved time resolution is mostly determined by the noise level and increasing the SADC sampling rate above 50 MHz will not improve significantly the performance of the system.

4.2.5. Rate performance

As mentioned in sections 1 and 2, 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 32. The rise time of the pulse is about 100 ns and the fall time is 25 μs. As described in section 4.2.1, the MWD digital filter differentiates the incom-
Figure 32: LNP preamplifier pulse shape before (thin solid line) and after single (thick dashed line) and double (thin dash-dotted line) MWD filtering for 80 ns (left panel) and 200 ns (right panel) differentiation time constants of the MWD filter.

Figure 33: The pulse height after single (solid line) and double (dashed line) MWD filtering as a function of the differentiation time-constant of the first MWD filter.

Figure 34: Measured cluster energy resolution for about 1 GeV photon energy obtained using the single (solid line) and double (dashed line) MWD filtering method. The energy resolution is plotted as a function of the differentiation time-constant of the first MWD filter.

short differentiating time-constants without increasing the noise level. Figure 33 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 34 the cluster energy resolution for γ-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.

5. Summary and outlook

PROTO60 is the first complete prototype of the PANDA EMC tested with high-energy tagged photons. Test measurements revealed a satisfactory performance. The measured energy and time resolutions fulfill the requirements set by the physics program of the PANDA experiment and summarized in the PANDA EMC Technical Design Report [2]. It is possible to obtain an energy resolution of 2.4 % at 1 GeV photon energy and sub-nanosecond time resolution for an energy deposition in the crystal above 80 MeV. This performance is achieved by using new PWO-II crystals cooled to -25 °C, large-area avalanche photodiodes and low-noise low-power preamplifiers. The test measurements were performed using two different readout schemes based on either the conventional charge-integrating readout or the Sampling ADC technique with digital signal filtering. The SADC readout has shown better performance in terms of energy resolution and the ability to operate the EMC at higher rates. The digital shaping of the signal allows to reduce the duration of the detector hit-response yielding a reduced pile-up probability of sequential pulses. In addition,
the precision of the extracted time stamp, using the digital implementation of the constant-fraction method, is sufficient to obtain a clean event correlation. Moreover, it is shown that the resolution is limited by the noise level and not by the method itself.

As described in section 2, in the final configuration the PANDA EMC will consist of three sub-detectors, namely, the EMC barrel and the forward and backward EMC endcaps. Each PWO-II crystal of the complete EMC, except the central part of the forward endcap, will be read out by two rectangular LAAPDs covering about 2 cm² of the crystal end-face. This larger coverage will lead to an improved photo-electron statistics and to an additional improvement of the resolution. Moreover, reading out each crystal by two independent photosensors connected to different readout channels will allow to detect and correct for the so-called nuclear-counter effect, i.e. when a high-energy charged particle penetrates the sensitive layer of the LAAPD producing a pulse of high amplitude. Such events will be detected by observing pulses from two sensors with very different amplitude. To accommodate the increased channel density and to reduce the power consumption a dedicated ASIC preamplifier APFEL has been designed [8]. At present, the next-generation EMC prototype equipped with APFEL preamplifiers, reading out two LAAPDs per crystal, is under construction.

This work demonstrates the advantages of the readout electronics based on the Sampling ADC technique. In addition to better performance, this approach allows to construct a triggerless data acquisition system. The digital data processing algorithms developed in this work were programmed in VHDL code to be implemented in an FPGA for on-line data analysis. A dedicated SADC hardware for the PANDA EMC is being developed with the aim to construct in the near future a prototype of a complete trigger-less readout chain.

Acknowledgements

The authors gratefully acknowledge the efforts of the MAMI-C accelerator crew for providing high-quality tagged photon beams. One of us (H. L.) wishes to thank the Nuclear Physics Institute at Rež / Prague for the warm hospitality in spring 2011. This work was supported in part by European Community-Research Infrastructure Activity under the FP6 Structuring the European Research Area programme (HadronPhysics contract number RII3-CT-2004-506078), by Bundesministerium für Forschung und Technologie (BMBF), Germany, by Gesellschaft für Schwerionenforschung (GSI), Darmstadt (Germany) and INTAS grant N2 06-1000012-8845.

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