The Forward Endcap of the Electromagnetic Calorimeter for the PANDA Detector at FAIR

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Abstract. The versatile $4\pi$-detector PANDA will be built at the Facility for Antiproton and Ion Research (FAIR), an accelerator complex, currently under construction near Darmstadt, Germany. A cooled antiproton beam in a momentum range of 1.5 – 15 GeV/c will be provided by the High Energy Storage Ring (HESR). All measurements at PANDA rely on an excellent performance of the detector with respect to tracking, particle identification and energy measurement. The electromagnetic calorimeter (EMC) of the PANDA detector will be equipped with 15744 PbWO$_4$ crystals (PWO-II), which will be operated at a temperature of $-25^\circ$C in order to increase the light output. The design of the forward endcap of the EMC has been finalized. The crystals will be read out with Large Area Avalanche Photo Diodes (LAAPDs) in the outer regions and with Vacuum Photo Tetrodes (VPTTs) in the innermost part. Production of photosensor units utilizing charge integrating preamplifiers has begun. A prototype comprised of 216 PbWO$_4$ crystals has been built and tested at various accelerators (CERN SPS, ELSA/Bonn, MAMI/Mainz), where the crystals have been exposed to electron and photon beams of 25 MeV up to 15 GeV. The results of these test measurements regarding the energy and position resolution are presented.

1. Introduction

The future accelerator complex FAIR will be built as an extension to the existing facilities of the GSI Helmholtzzentrum für Schwerionenforschung near Darmstadt, Germany. The PANDA experiment is one of the approved key experiments at this facility, which will make use of a secondary antiproton beam. The detector will be mounted at an internal target position of the HESR, which will provide a cooled antiproton beam with a precise definition of the beam energy in a momentum range of 1.5 - 15 GeV/c. Due to the interaction of the antiprotons with protons of an internal target a luminosity of up to $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ will be achieved, while the beam momentum resolution will be as good as $\Delta p/p = 4 \times 10^{-5}$. The main focus of the experiment lies on hadron spectroscopy, especially the search for exotic states in the charmonium mass region. Other goals from the broad spectrum of accessible physics cover the interaction of hadrons with nuclei as well as electromagnetic processes, which will lead to a better understanding of the nucleon structure [1].

Since PANDA is a fixed target experiment, a large fraction of the scattered and produced particles will be emitted under small azimuthal angles with respect to the beam axis and direction. Therefore the PANDA spectrometer is split into a target spectrometer based on a 2T superconducting solenoid magnet, which is surrounding the interaction point, and a forward...
Figure 1. Technical drawing of the PANDA detector. The electromagnetic calorimeter systems in the target spectrometer are depicted in a violet color.

spectrometer, which contains a 2 Tm dipole magnet. A sketch of the PANDA detector is shown in Fig. 1. Both the target and the forward spectrometer contain subdetectors for charged particle identification, tracking, electromagnetic calorimetry and muon identification.

1.1. The PANDA Electromagnetic Calorimeter
The physics program of the PANDA experiment sets high demands on the performance of the electromagnetic calorimeter systems. A photon reconstruction threshold of 10 MeV is a central requirement, which leads to a single crystal threshold of about 3 MeV and a corresponding noise level equivalent to 1 MeV. These requirements are justified by the need to efficiently measure low-energy photons in order to make the reconstruction of final states involving many photons possible. This is especially important for the envisaged precision spectroscopy of charmonium states and exotic hadrons in the charmonium region. The most abundant sources of final state photons are $\pi^0$ and $\eta$ mesons, which must be clearly identified in order to separate them from single photons occurring e.g. in radiative charmonium decays.

In the Forward Spectrometer a sampling-type "shashlyk" calorimeter using lead absorbers and plastic scintillator tiles, that are read out via wavelength-shifting fibres with photomultipliers will be installed in order to cover the most forward part of the solid angle. This part of the EMC is described in more detail in [2].

The EMC in the Target Spectrometer is a homogeneous crystal calorimeter utilizing 15744 lead tungstate crystals (PbWO$_4$). This material has been chosen due to its compactness, fast response, short decay time and radiation hardness. The material used for the PANDA crystals is denoted as PWO-II, a second generation of lead tungstate material in comparison to the first generation material used e.g. in the calorimeter of the CMS experiment at the LHC. The main improvement is the significantly higher light yield that one can gain for PWO-II crystals [3]. A comparison of the two materials is given in Table 1.

The PANDA EMC will consist of a cylindrical barrel part comprised of 11360 crystals, a forward (3856 crystals) and a backward endcap (528 crystals). While all crystals will have a
Table 1. Characteristics of PWO-I and PWO-II crystals [4]

| Characteristic                                           | PWO-I (CMS) | PWO-II (PANDA) |
|----------------------------------------------------------|-------------|---------------|
| La, Y concentration level (ppm)                          | 100         | 40            |
| Light yield of full size (20cm) crystal with PMT-readout at room temperature (phe/MeV) | 8 – 12      | 17 – 22       |
| Light yield temperature coefficient at $T = +20^\circ$C (%/K) | −2.0        | −3.0          |
| EMC operating temperature ($^\circ$C)                    | +18         | −25           |

length of 200 mm, which is equivalent to 22 times of the radiation length of PWO-II, the tapering of individual crystals differs with the position of the crystal in the calorimeter. The crystals in the endcaps are only slightly (forward endcap) or not tapered at all (backward endcap), while crystals foreseen for the barrel part are produced in eleven different geometrical shapes. In order to increase the light output of the crystals roughly by a factor of four compared to operation at $T = +25^\circ$C, the EMC will be operated at a temperature of $-25^\circ$C. All crystals are pointing off the asymmetrically located target position. The crystals in the barrel and backward endcap part of the EMC will be read out with each two Large Area Avalanche Photodiodes (LAAPDs), while a readout partly with LAAPDs and partly with Vacuum Photo Tetrodes (VPTTs) is foreseen for the forward endcap, which is discussed in more detail in Section 2. One reason for the use of these types of photosensors is their tolerance regarding an external magnetic field, since the EMC will be placed inside the 2 T superconducting solenoid in the target spectrometer. An energy resolution of $\sigma_E / E = 1\% \oplus 2\% / \sqrt{E[ GeV]}$ and a time resolution better than 2 ns should be achieved with the PANDA EMC. A technical drawing of the barrel and forward endcap part of the EMC is shown in Fig. 2. [6]

Figure 2. Schematic drawing of the barrel- and forward endcap part of the PANDA EMC. The crystals in the forward endcap are depicted in orange, covered by a thermal insulation shown in green.
2. The Forward Endcap of the PANDA-EMC

The geometrical shape of the Forward Endcap is that of a disc with an asymmetrical opening in the center, through which the beam pipe will be led. Particles passing the opening will be detected in the forward spectrometer. Thus, the forward endcap covers the angular range between $5^\circ$ and $23.6^\circ$ in vertical, and $10^\circ - 23.6^\circ$ in horizontal direction. The components used in this part of the detector have to withstand some extremely challenging environmental conditions. Due to the Lorentz-Boost in a fixed target experiment, the single crystal hit rate in the forward endcap is expected to be much higher (up to $1 \cdot 10^6 s^{-1}$ for the innermost crystals) than in the barrel and backward parts of the detector. A radiation dose of up to 125 Gy per year will be accumulated when running at the full design luminosity of $2 \cdot 10^{32} cm^{-2}s^{-1}$. Furthermore, the magnetic field in this region of the target spectrometer will be as high as 1.2 T. These conditions, together with the operating temperature of $-25^\circ$C require a robust design of the electronics and photosensors placed in the cold volume. The proper detection of signals from the energy threshold of 3 MeV up to a 12 GeV maximum photon energy deposition per single crystal must be ensured. Due to the large dynamic range, radiation dose and rate a low-power, low-noise charge integrating preamplifier has been designed for the forward endcap, which will be attached directly to the photosensors at the back of each crystal [7].

Since not only the light yield of the PWO-II crystals, but also the characteristics of the photosensors, especially those of the LAAPDs, are strongly temperature dependant, a precise temperature monitoring system has been developed for the PANDA-EMC, called the THMP (Temperature and Humidity Monitoring board for Panda) [8]. Ultrathin platinum-wire temperature sensors (thickness < 200 µm) are placed inbetween the crystals and read out using the microcontroller driven THMP board in order to monitor the temperature inside the forward endcap at the location of the crystals [9]. Three independantly controllable cooling circuits are used for the temperature stabilization of the volume that contains the PWO-II crystals. The front insulation contains plates with meander-shaped grooves, through which dried and

Figure 3. This exploded assembly drawing shows the main constructional parts of the forward endcap. The PWO-II crystals are not depicted in this drawing.
cooled air will be pressed. This provides cooling of the crystals from the front side, whereas the outermost ring of crystals will be cooled by pipes that follow the outer shape of the endcap and carry a cooled liquid (methanol-water mixture). The largest fraction of cooling power is being transported by the so called backplate, an aluminium plate that has a thickness of 30 mm and a diameter of 2 m. All crystal units, containing in total 3856 crystals, will be mechanically attached to this backplate using aluminium mounting structures, so that heat transport through conduction can be used here. A liquid methanol-water mixture is pumped through long vertical holes inside the backplate. This provides the most efficient cooling of the crystals from their back side. All cooling systems and the backplate can be seen in Fig. 3.

2.1. Crystal subunits

Each PWO-II crystal is wrapped in DF2000MA [5], a highly reflective foil, in order to reflect as much of the scintillation light as possible back into the crystal. At the back face of the crystal a cutout in the reflective foil with the size of the active area of the photodetector is left for the scintillation light to leave the crystal. LAAPDs as well as VPTTs are glued to the crystal using the room temperature vulcanizing silicone based adhesive Dow Corning 3145. The preamplifiers are directly soldered to the photodetectors. In total 16 of these crystal-photodetector-preamplifier units are mechanically held together by a carbon fibre alveole. The ultrathin temperature sensors are affixed to the side faces of selected crystals before they are sled into the alveole. The electrical connections of the temperature sensors are fed out at the back of the subunit, together with the signal and supply cables for the photodetector units (see Fig. 5). Aluminium mounting structures are pushed into the carbon fibre alveoles at their rear end in order to mechanically stabilize the positions of the photodetectors and enable the subunit to be mounted to the backplate. This 4 × 4 matrix is called a subunit. A technical drawing as well as a photograph of a fully equipped prototype subunit are depicted in the Figures 4 and 5.

Figure 4. Technical drawing of a 16-crystal subunit mounted to the aluminium backplate. For illustration of the mounting mechanics the side face of the subunit has been removed.

Figure 5. Photograph of a prototype subunit equipped with 16 VPTT readout units. The mounting structure has not yet been fully attached.
2.2. Photodetectors

The innermost 768 crystals of the forward endcap will be equipped with Vacuum Photo Tetrodes (R11375-MOD) of the Japanese manufacturer Hamamatsu. VPTTs are small, two-stage photomultipliers with an active area of $\approx 200 \text{mm}^2$, a diameter of 23.9 mm and a length of 40 mm. All electrodes and dynodes are oriented in parallel to the front face of the glass tube, so that one dynode as well as the anode had to be designed as a mesh in contrast to a solid electrode (see Fig. 6). After delivery different parameters for each VPTT are being measured in order to ensure proper operation and reproduction of the manufacturer’s values. The absolute amplification of the VPTTs is determined by an explicit measurement of the anode and cathode current while the VPTT is being illuminated with constant light. Furthermore the dark current for each tube is measured. The magnetic field strength will be about 1 T at the position of the VPTTs, which will result in a drop of the gain by about 50% (see Fig. 7). The extremely good radiation hardness in combination with the small detector capacitance of $\approx 22 \text{pF}$ led to the choice of this photodetector type for the innermost crystals, for which the highest radiation doses and peak rates are expected.

The outer 3088 crystals will be read out with two rectangular Large Area Avalanche Photodiodes (S11048, Hamamatsu) each. The active area of one PANDA-LAAPD is $(6.8 \times 14) \text{mm}^2 = 95.2 \text{mm}^2$, so that the sensitive area of two APDs is comparable to that of a VPTT. The functionality of APDs is largely independent of the strength of an external magnetic field, but the capacity of these photodetectors is about ten times higher ($\approx 270 \text{pF}$) than for a VPTT. Due to the avalanche effect, an APD has an internal signal amplification, dependant on the applied bias voltage. Thus, each APD has to be operated at the proper bias voltage to realize operation at the same gain ($M$). However, the gain of these semiconductor devices is strongly temperature dependent, so that the response curve for each APD has to be measured for different temperatures prior to gluing the photosensor to a crystal. The response curve of one APD measured at $T = +25^\circ \text{C}$ and $T = -25^\circ \text{C}$ is shown in Fig. 9. In the forward endcap the APDs will be operated at $T = -25^\circ \text{C}$ and a gain of $M = 200$. At this point the slope of the response curve reaches a value of $\frac{dM}{dT} / dU \approx 6.5 \% / V$, while the dependence of the operating temperature is $\frac{dM}{dT} \approx 1.5 \% / K$. Due to this dependence it is of utmost importance also for the operation of the photodetectors to have a precise temperature measurement inside the forward endcap. Fig. 8 shows a photograph of the front face of two LAAPDs and a functional diagram.

![Figure 6: Photograph and functional drawing of a VPTT](image)

![Figure 7: Dependence of the relative VPTT gain from the applied external magnetic field for different mounting positions given in terms of the azimuthal angle $\Theta$.](image)
3. Forward endcap prototype setup

A prototype of the forward endcap comprised of 216 full-sized PWO-II crystals has been built. Geometrically the prototype resembles a cutout of the forward endcap near to the asymmetrical hole in the center of the detector (see Fig. 10). Both detector types foreseen for the forward endcap have been used to read out crystals in the prototype, which have been cooled down to the operating temperature of $T = -25^\circ$C. The prototype is being used to estimate the expected performance of the PANDA-EMC in a most realistic scenario. Tests of the mechanical components and assembly procedure, the cooling and temperature readout systems, the photosensor readout electronics and the slow control could be performed in the lab as well as at various accelerator facilities. At testbeams the crystals have been exposed to electron and photon beams in order to determine the achievable performance in terms of noise, energy resolution, minimal energy threshold and spatial resolution. An overview over the different testbeams is given in Table 2. All photodetectors are attached to the PANDA low noise preamplifiers discussed in Section 2. The signals are then fed to custom VME shaper modules with a shaping time of 100 ns and finally digitized using commercial VME sampling ADCs.
Table 2. Testbeams with the forward endcap prototype

| Beam particles | $E_{\text{Beam}}$ or $p_{\text{Beam}}$ | Specialties |
|----------------|-------------------------------------|-------------|
| CERN/SPS $e^+$ | 10, 15 GeV/c | max. PANDA energy; |
| $\mu^+$ | 150 GeV/c | dep. energy $\approx$ 230 MeV |
| ELSA/Bonn Tagged $\gamma$ | 1, 2.1, 3.1 GeV | Rates up to $2 \cdot 10^6$ s$^{-1}$ |
| MAMI/Mainz Tagged $\gamma$ | 20 – 415 MeV | excellent beam energy resolution |
| CERN/SPS $e^-$ | 5 – 15 GeV/c | Fibre / Si-strip |
| $\pi^+, K^+, \bar{p}$ | 15, 50 GeV/c | TrackingStation |

(WIENER AVM16, Struck SIS3302). A detailed model of the prototype was implemented in Geant 4 [11], including dead material (aluminium mechanics, alveoles, insulation, cooling tubes + liquid, ...) and the correct alignment of the prototype axis to the beam axis, according to measurements performed at the testbeams. Whenever possible, the beam profile was also measured using fibre hodoscopes ($e^\pm$ beam) or a beam camera (photon beam), and properly included into the simulation.

Single crystal energy deposits for centrally impinging particles at different beam energies have been used to calibrate each single readout unit. The most probable value for the energy deposition has been determined from the Monte Carlo simulation. After applying the same cuts to testbeam data the corresponding ADC conversion for the most probable value has been determined. This procedure is repeated for each available beam energy. Afterwards a polynomial fit is performed in order to obtain a calibration function ($E_{\text{dep}}(\text{ADC Conversion})$) for each readout unit.

3.1. Results from testbeams

3.1.1. Noise and Threshold

The best performance regarding energy equivalent noise has been measured for the Vacuum Photo Tetrodes. A mean noise of $\langle \sigma_{\text{Noise}} \rangle_{\text{VPTTs}} = 1.6 \text{ MeV}$ has been determined, which is near the envisaged value of 1 MeV in the Technical Design Report of the EMC [6]. For the APDs a slightly worse value of $\langle \sigma_{\text{Noise}} \rangle_{\text{APDs}} = 2.2 \text{ MeV}$ has been measured.

In order to determine the optimal value for the single crystal energy threshold ($E_{\text{thr}}$), the dependance of the energy resolution for a $3 \times 3$ crystal matrix has been studied in dependance of $E_{\text{thr}}$. For this scan the threshold has been varied in the range of $1 – 15 \text{ MeV}$. Fig. 11 shows threshold scans exemplary for two different beam energies. The best resolution can be obtained by applying a single crystal threshold of 5 MeV, which corresponds roughly to $3 \cdot \langle \sigma_{\text{Noise}} \rangle_{\text{VPTTs}}$.

3.1.2. Energy resolution

For the PANDA PWO-II crystals about 80% of the incident energy is deposited in the crystal that is centrally hit by a particle. In order to reconstruct the incident energy, the deposition in many crystals is summed up. For the prototype studies the deposition in symmetrical $3 \times 3$ or $5 \times 5$ crystal matrices is used. Due to the fact that electromagnetic showers can have asymmetrical shapes and large fluctuations, later an algorithm will be used to select crystals that contribute to the shower, starting from the crystal with the largest deposition and subsequently moving outwards until crystals are reached, for which the deposition lies below the threshold $E_{\text{thr}}$.

For each beam energy the resolution is determined from a fit to the distribution of the energy sum. This distribution has an asymmetrical shape, which can be described by a gaussian function with an additional tail towards lower energy deposits. The empirically determined function for
Figure 11. Energy resolution vs. applied single crystal threshold shown for two different beam energies (tagged photons, MAMI testbeam). The optimal energy threshold determined by this is $E_{\text{thr}} = 5\,\text{MeV}$ (measured with VPTTs).

this distribution is described in more detail in [10]. The resolution is determined from the width $\sigma_E$ of the fitted function and the energy of the incident particle $E$ as $\sigma_E/E$. The width is defined as $\sigma_E = \text{FWHM}/(2\cdot\sqrt{2}\ln 2)$. Examples for the energy deposition in the central and surrounding crystals as well as the sum are shown for a low ($E = 295.14\,\text{MeV}$) and a high ($E = 10.0\,\text{GeV}$) beam energy in Fig. 12 and 13, respectively.

Figure 12. Energy deposition in the central crystal, the surrounding ring of crystals and the sum of all nine crystals at a beam energy of $E = 295.14\,\text{MeV}$. The energy sum has been fitted to obtain the energy resolution (measured with VPTTs).
Figure 13. Energy deposition in the central crystal, the surrounding two rings of crystals and the sum of all 25 crystals at a beam energy of $E = 10.0 \text{ GeV}$. The energy sum has been fitted to obtain the energy resolution.

Figure 14. Energy resolution as a function of beam energy. The blue curve shows the envisaged energy resolution.

The resolution has been determined for incident energies in the range of 25 MeV up to 15 GeV for the different photodetector types. All results are summarized in Fig. 14 together with the envisaged energy resolution function given in the Technical Design Report [6] (blue curve). For small energies the resolution is slightly worse than the targetted value, while for the highest energies expected in the PANDA experiment the expectations can be met very well.
3.1.3. Spatial resolution

The position resolution of the forward endcap prototype could be studied at the CERN testbeam, due to the use of Si-microstrip detectors with a pitch of 50 \( \mu \text{m} \) and a fibre hodoscope, that were set up in front of the prototype. The point on the surface of the central crystal, at which a beam particle hit the crystal, can be reconstructed from the information of the tracking detectors as well as from the measured energy depositions in the prototype. A logarithmic weighting method was used to calculate the point of impact from the energy deposition in the crystals. The difference between the point of impact calculated from the energy deposition and tracking detectors, denoted as \( \Delta x \), shows the spatial resolution (Fig. 15). The width of this gaussian shaped distribution, \( \sigma_x \), was determined for all four beam energies. The resolution was determined to be \( \sigma_x = 1.6 \text{ mm} \) at \( E = 5 \text{ GeV} \) (black curve in Fig.15) and subsequently decreases to 0.9 mm at an Energy of 15 GeV (blue curve). The resolution for the intermediate energies were measured as \( \sigma_x = 1.3 \text{ mm} \) at \( E = 7.5 \text{ GeV} \) (red curve) and 1.1 mm at an energy of 10 GeV. These results are in good agreement with the design value for the forward endcap of \( \sigma_x, \text{TDR} < 3.5 \text{ mm} \). Additionally the dependance of the position resolution from the point of impact along the front face of a crystal has been studied. It was found, that the resolution improves towards the borders of the crystal. In these cases the largest fraction of the energy is deposited in two crystals instead of only the central crystal. This behaviour could also be qualitatively reproduced with Monte Carlo simulations (see Fig. 16: red curve: simulation, black: testbeam data). Along the front face of the crystal the position resolution is about a factor of three better than the targetted design value for all points that were studied.

\[ \begin{align*}
\text{Figure 15.} \quad & \text{Position resolution for different beam energies. The distribution is shifted from the center for higher beam energies due to the non-zero angle between the crystal- and beam-axis.} \\
\text{Figure 16.} \quad & \text{Position resolution as a function of the point of impact on the crystal surface for testbeam data (black) and Monte Carlo simulation (red). The vertical lines indicate the borders of the central crystal.}
\end{align*} \]

Acknowledgments

We wish to thank the staff of the SPS (CERN), ELSA (U Bonn) and MAMI (U Mainz) accelerators for their support and help during the forward endcap prototype testbeams.

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