Construction of the Forward Endcap Calorimeter of the PANDA Experiment at FAIR

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Abstract. PANDA is the main hadron physics addressing experiment of the future FAIR (Facility for Antiproton and Ion Research) center at Darmstadt, Germany. Located at the HESR antiproton storage ring the PANDA detector is optimized for physics of the weak and strong interactions in the charm sector: Search for new and exotic states of matter, precise determination of quantum numbers, masses and widths of hadronic resonances and deeper insights into the structure of hadrons. The detector consists of a target spectrometer built around the interaction region, where antiprotons carrying momenta of 1.5-15 GeV/c collide with a fixed hydrogen target, and a forward spectrometer. Its design is based on compactness and cost saving while achieving high resolution, rate capability and physics selectivity. In the PANDA target spectrometer the electromagnetic calorimeter is composed of three subdetectors based on lead tungstate crystals operated at $-25^\circ$C. A barrel structure built from 11360 crystals will be closed in up- and downstream direction by two endcaps containing 524 and 3856 crystals, respectively. After intense beam test phases with a 200 crystal forward endcap prototype the required performance was shown to be met and the design finished. The upstream located forward endcap is currently under construction. Besides the overall mechanical design and cooling concept the 16-crystal submodules series manufacturing and quality assurance measures are presented.

1. Introduction
The PANDA experiment is part of the accelerator complex FAIR currently being built as an extension of GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany. The PANDA detector will be located at the HESR synchrotron storage ring providing cooled antiprotons in the momentum range of 1.5 GeV/c to 15 GeV/c. In conjunction with an internal hydrogen target luminosities of up to $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ and beam momentum resolution of $\Delta p/p = 4 \times 10^{-5}$ will be achieved.

The main focus of the PANDA experiment is hadron spectroscopy, especially the search for exotic states in the charmonium mass region. The physics program also comprises open charm and baryon spectroscopy, studies of hadron-nuclei interactions and electromagnetic processes leading to an improved understanding of the nucleon structure [1].

As a fixed target experiment the corresponding PANDA detector is divided into a target and a forward spectrometer part as shown in Fig. 1.

The PANDA target as well as the forward spectrometer contain subdetectors for charged particle identification, tracking, electromagnetic calorimetry and muon identification.
Figure 1. Drawing of the PANDA detector with the purple colored electromagnetic calorimeter subdetectors.

Table 1. Characteristics of PWO-I and PWO-II crystals [3].

| 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) | $-2.0$      | $-3.0$         |
| Operating temperature ($^\circ$C)                  | $+18$       | $-25$          |

1.1. The PANDA Electromagnetic Calorimeter

Of utmost importance in the PANDA physics program is the full reconstruction of multi-photon and lepton-pair decay channels. Therefore a low particle energy detection threshold of 10 MeV is necessary. The calorimeter needs to ensure good energy and spatial resolutions for photons up to 15 GeV and full angular coverage for high yield and background rejection properties. The target spectrometer part is built as a homogeneous calorimeter in the shape of a barrel closed by two endcaps containing about 16000 lead tungstate crystals. In the forward spectrometer a Shashlyk type sampling calorimeter built from lead absorbers and plastic scintillators is used.

The crystal material for the target calorimeters is an improved lead tungstate (PWO-II) [2]. Chosen for its fast response and radiation hardness this variant outperforms the earlier type PWO-I in light yield as well as radiation hardness as given in Table 1.

The crystal length is 200 mm corresponding to 22 radiation lengths. Tapering of the crystals varies with position (angle to the beam axis) and is minimal in the forward endcap. There is no tapering of the crystals in the backward endcap. The target calorimeter is foreseen to
operate at a temperature of $-25^\circ$C in order to substantially increase the light yield of the scintillator material. All crystals are arranged in off-pointing position to the interaction point. Readout of the scintillators is accomplished by two large area avalanche photo diodes (APDs) on every crystal. The very inner part of the forward endcap, which is exposed to a high radiation dose, is comprised of 768 crystals, which are instead read out by one vacuum photo tetrode tube (VPTT), each. Setting inside the target spectrometer magnet the photo tubes will loose half their gain which is considered and acceptable with respect to the achievable performance while the APDs are not affected by the solenoid field at all. Energy and time resolution of $\sigma_E/E = 1\% \oplus 2\%/\sqrt{E[GeV]}$ and better than 2 ns, respectively, is the design objective to be achieved with the PANDA target calorimeter [6]. A technical drawing of the PANDA target electromagnetic calorimeter is shown in Fig. 2.

2. The Forward Endcap of the PANDA Calorimeter

In the forward endcap (Fig. 3) the crystals are mounted on a plane support disc. This backplate has drilled tubes in vertical direction the coolant liquid is flowing through. Through the center of the forward endcap the beam pipe is passing. The angular coverage therfore is between $5^\circ$ and $23.6^\circ$ in vertical, and $10^\circ$ to $23.6^\circ$ in horizontal direction.

Single crystal hit rates in the forward endcap are highest in the center region around the beam pipe hole and range up to $10^6$ s$^{-1}$ for the innermost crystals. A corresponding radiation dose of up to $125 \text{ Gy per year}$ will be accumulated when running at the full design luminosity of $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

3. Prototype Beam Measurements

Prior to the construction of the forward endcap of the PANDA target electromagnetic calorimeter a prototype representing a cutout of the full detector was build. It contained about 200 crystals arranged in submodules of 16 or 8 crystals each. Performance tests with different types of photo detectors (APD, photo triodes and tetrodes) from different manufacturers at different laboratories have been conducted. The response of the detector to different particle beams over the whole PANDA energy range was tested. There have been two beam times at CERNs SPS with electrons, muons and mixed hadron beams in the energy range above 5 GeV. At the

![Figure 2. The PANDA target electromagnetic calorimeter: A barrel structure closed by two endcaps.](image-url)
Table 2. Test beams with the forward endcap prototype [7].

| Beam particles | $E_{Beam}$ or $p_{Beam}$ | 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 |

electron accelerators ELSA in Bonn and MAMI in Mainz measurements with tagged photons in the medium and low energy range with high rates and/or excellent beam resolution have been done. An overview of the test beams is given in Table 2.

Fig. 4 compares the required energy resolution as a function of particle energy with the results derived from the prototype beam time measurements. In the high energy range the requirements could already be met while in the low and medium energy range the performance of the prototype needs to be exceeded. With several improvements of the forward endcap design the PANDA requirements over the whole energy range will be fulfilled. These improvements are tight couplings of photo detectors and crystals as described in this article. In the forward endcap prototype the couplings needed to be realized in a reversible way in order to allow a reuse of all the crystals involved. Several modifications were done in the electronic readout chain. The optimum gain of the APDs with respect to a balance of signal to noise performance and sensitivity to changes in temperature and high voltage was determined. The corresponding necessary gains both of the APDs and the tube preamplifiers to optimal cover the dynamic range could be derived and the input shaper stages on the ADC boards optimized accordingly.

4. Submodules
In the forward endcap the crystals are mounted in submodules of 16 or 8 crystals each combined in lightweight yet precise and stable carbon fibre aleveoles. Those are connected to the planar

Figure 3. The forward endcap of the PANDA target electromagnetic calorimeter and its off-pointing geometry.
backplate by individual interface pieces providing the correct angle of slope with respect to the position in the forward endcap.

4.1. Photo Sensors
The very inner, high radiation exposed part of the forward endcap is equipped with vacuum photo tetrodes, type Hamamatsu R11375-01, with about 20 % quantum efficiency and a gain around 50, diminishing to about half that value when operated in the maximum magnetic field in the forward endcap of 1.2 T. The active sensor area is 200 mm$^2$, the detector capacitance is about 22 pF. In the remaining part of the target spectrometer a pair of APDs, type Hamamatsu S11048, is used for readout. With a quantum efficiency of about 80%, active areas of 100 mm$^2$, a detector capacitance of 270 pF, and a gain set to 200 by choice of the supply voltage gives very similar performance for both types of photo sensors in conjunction with their respective preamplifiers.

4.2. Readout Units
Units of photo sensors and corresponding preamplifiers are referred to as readout units. The preamplifiers are specifically designed for both types of photo sensors [8]. The electrical circuits are similar while the mechanical shape differs to compensate for the different space consumptions of the photo detectors. In case of the VPTTs there is a single preamplifier sitting almost rectangular on a round voltage divider PCB that is directly soldered to the photo tubes. The supply voltage of nominal 1 kV is divided into the different dynode supply voltages. For the APD readout one preamplifier each is used, so a package of two is mounted back to back mechanically connected to the APD pair by a capsule interface as shown in Fig. 5. As the APD gain is set by the operating voltage all APD preamplifiers have one fixed gain, whereas the VPTT preamplifiers come in three different gain variants in order to adjust proper response depending on individual crystal light yield and tube gain. The VPTT readout units finally are encapsulated by shrinking tube and the remaining volume filled with silicon casting compound acting both as a mechanical protection as well as a prevention from moisture build up on the high voltage electronics. Electrical shielding is accomplished by self adhesive copper and aluminum tape connected to the preamplifier ground. The APD readout units are covered by aluminum tubes acting as electrical and mechanical shield filled with casting compound and closed by aluminum tape on the rear side where the cables enter.

![Figure 4. Energy resolution as a function of particle energy achieved with the 200-crystal prototype in comparison to the PANDA calorimeter performance demand (dashed curve) [7].](image_url)
4.3. Crystal Units

Single crystals covered with reflective foil and glued to a readout unit represent a crystal unit. The reflective foil of type DF2000MA by 3M [4] is laser cut and grooved for easy handling. The readout side has specific cutouts for VPTTs and APDs covering all but the area corresponding to the active photo sensor region. Therefore the foil has to cover the crystal before the readout units can be glued to the readout side. The requirements to the adhesive are quite complex. It has to ensure a radiation hard optical transparent coupling withstanding 50 K of temperature difference between mounting and operation temperature yet being sufficiently flexible to moderate the different thermal expansion coefficients of the materials involved (lead tungstate, silica glass, epoxy). The extreme smooth surface of the polished crystals is an additional challenge. The silicon adhesive Dow Corning RTV 3145 is able to fulfill these requirements as long as a special primer fluid of the same manufacturer is used to condition the crystal surface prior to gluing. The gluing process comprises application of the proper amount of glue by a pneumatic applicator, curing of the adhesive while the coupling is pressurized. An aligning suspension taking crystal and readout unit is fixing the crystal unit during curing of the adhesive of one week. The coupling is checked and documented by surveillance with a digital camera. The front face of the reflective foil cover therefore is folded back to allow a view to the coupling through the crystal. There is a time window of approximately 20 hours, depending on humidity as the adhesive is moisture curing, for a removal of the glue in case the coupling is not in order.

4.4. Stimulated recovery LEDs

During preparation of the crystal units one blue LED per crystal will be mounted to the units. The purpose of this LEDs is an illumination of the crystal with light of the same wavelength as the scintillation light of lead tungstate in order to stimulate a recovery of the crystals from radiation induced damages to the crystal transparency [5]. In case of the VPTT units the LEDs are glued besides the VPTT unit into one corner of the crystal readout face in the same gluing process, while the LEDs for the APD read out crystals are mounted during the readout unit construction and glued to the APD capsules.

5. Temperature Monitoring

As both crystal light yield and APD gains are temperature dependent properties of the calorimeter a precise monitoring and regulation based on it is mandatory. The design value is a precision of 0.1 °C with a resolution of 0.02 °C. In order to allow for temperature measurements inside the scintillator volume, that is in between the crystals, there is the need for very thin temperature sensors not exceeding 150 µm total thickness. Since there is no commercial supplier of temperature sensors with this dimension a series production of specially developed platinum
wire sensors sitting on a Kapton foil and correspondingly thin four-wire flat cables has been started. The widths of the sensors is less than 20 mm in order to be able to place it on a crystal side face. Fig. 6 shows a crystal unit equipped with a temperature sensor at the front of its upper side. Each submodule is intended to be equipped with two such temperature sensors resulting in a total demand for 500 sensors for the forward endcap of the PANDA target calorimeter. Dedicated 64-channel 14-bit ADC readout boards have been developed. In order to meet the required resolution a calibration of sensors and boards is necessary.

6. Digitization
Signals from the readout unit’s preamplifiers are single ended fed to 64 channel 80 MHz sampling ADC boards with 14-bit resolution and analog shaping input stages with high/low gain splitting. The boards contain two Kintex-7 FPGAs for online feature extraction and two optical SFP interfaces with 2 Gbit/s rate capability and are sitting in dedicated cooling crates inside the forward endcap support frame. In total 220 boards are needed for the forward endcap readout.

7. Monitoring System
A light pulser system based on 10 pulser modules located in the forward endcap support frame monitors the light yield loss of the individual crystals, allows for linearity checks of the readout chain and serves as a diagnostics tool during setup and PANDA run time. The LED pulser modules mimic the scintillation light pulses of lead tungstate (Fig. 7) over the full dynamic range by means of LCD attenuators which guarantee a compact design to fit into the support frame and without the need for regular maintenance.

A reference system monitors the intensity of every single light pulser module by comparison of their fibre coupled light signals with those generated by a $^{22}Na$ source in a LaBr$_3$(Ce) crystal. The scintillation pulse shape of LaBr$_3$(Ce) is very close to the one of PbWO$_4$ so the same readout electronics can be used for the reference pulses. The much higher light yield of LaBr$_3$(Ce) does not require the reference system to operate at the calorimeter operation temperature. In total about 30 km of silica/silica fibres feed the monitoring light pulses to the readout side of each crystal where it is injected via spring loaded air coupling. A dedicated routing scheme with respect to approximate equal fibre lengths was made.

8. Mechanics and Cooling
The detector backplate, the submodules are attached to, is surrounded by the crates for the ADC boards and the light pulser modules sitting in the support frame surrounding and suspending the cold volume. Cooling is accomplished via bores in the backplate, cooling pipes running across the side walls, and by thin hoses in front of the crystals. The cold volume is surrounded by aluminum plates thermally equalizing the boundery surfaces and electrically shielding the...
Figure 7. Comparison of LED and scintillation pulse shape at preamplifier output.

active detector volume. An isolation layer of vacuum insulation panels (VIPs) ensures the most effective thermal shielding possible in the given space for insulation material. Two layers of VIP panel tiles with overlaying joints minimizes thermal bridging.

Cooling of the forward endcap is established by a central cooling machine supplying all three parts of the target calorimeter with coolant. Its reservoir temperature is choosen to be some degrees below the operating temperature of -25° C of the scintillators. A sufficiently fast temperature regulation is then realized by controlled heating of the different subcircuits.

A mechanical test beam and transportation frame for the complete forward endcap is installed in the COSY TOF area at FZ Jülich where the endcap will be equipped with submodules in 2018/2019.

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