

# Setup and COSY Proton Beam Tests of the PANDA Forward Endcap Calorimeter at FAIR

Thomas Held<sup>1\*</sup>

<sup>1</sup>Institut für Experimentalphysik I, Ruhr-Universität Bochum, Universitätsstr. 150, 44801 Bochum, Germany

**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 in the structure of hadrons. The detector consists of a target spectrometer built around the interaction region of antiprotons carrying momenta of 1.5-15 GeV/c 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 degrees 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. The upstream located forward endcap has been completed with vacuum photo tetrode read-out crystal submodules and was operated at two beam times in 2023 at the Juelich Cooler Synchrotron with a 2.5 GeV/c proton beam. Besides the detector setup, the cooling concept, and beam test results will be presented.

## 1 Introduction

The PANDA experiment is part of the accelerator complex FAIR currently being built 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  $2 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1}$  and beam momentum resolution of  $\Delta p/p = 4 \cdot 10^{-5}$  will be achieved.

The main focus of the PANDA experiment is hadron spectroscopy, especially the search for exotic states in the charmonium mass region [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.

### 1.1 The PANDA Electromagnetic Calorimeter

The full reconstruction of multi-photon and lepton-pair decay channels require a low particle energy detection threshold of 10 MeV. 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.

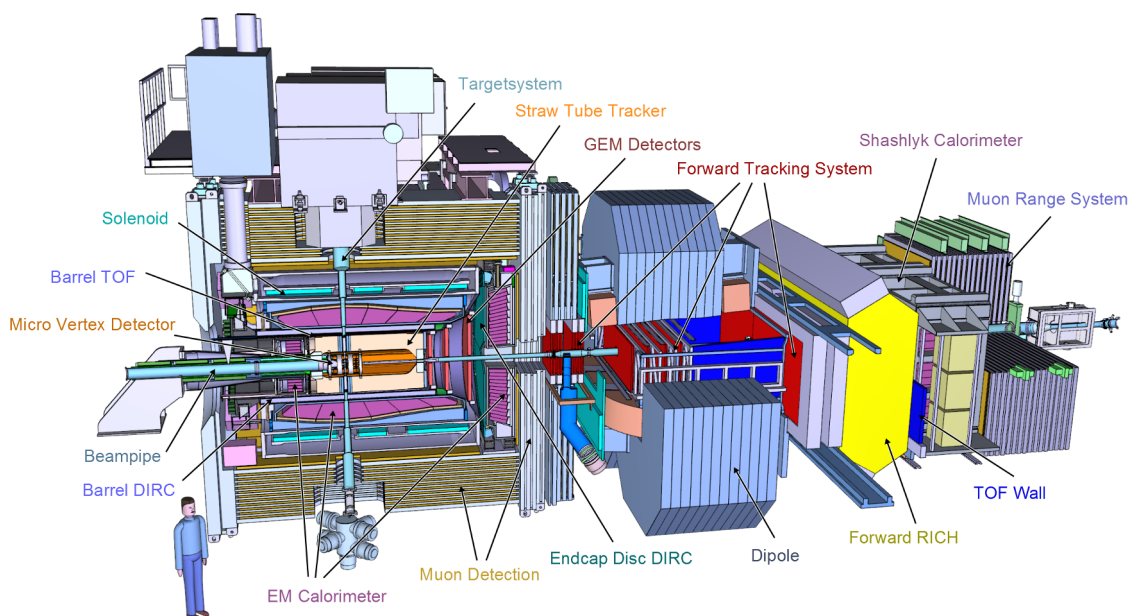
**Table 1.** Characteristics of PWO-I and PWO-II crystals [3].

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 coeff. at $T = +20^\circ\text{C}$ (%/K)	-2.0	-3.0
Operating temperature ( $^\circ\text{C}$ )	+18	-25

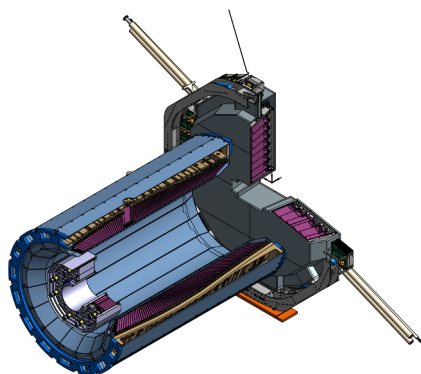
The crystal material for the target calorimeters is an improved lead tungstate (PWO-II) [2]. Chosen for its fast response and radiation hardness this variant outperforms the earlier type PWO-I in light yield as well as radiation hardness as given in Table 1.

The crystal length is 200 mm corresponding to 22 radiation lengths. Tapering of the crystals varies with position and is minimal in the forward endcap. The target calorimeter is foreseen to operate at a temperature of  $-25^\circ\text{C}$  in order to substantially increase the light yield of the scintillator material. All crystals are arranged in off-pointing position to the interaction point. Energy and time resolution of  $\sigma_E/E = 1\% \oplus 2\% / \sqrt{E[\text{GeV}]}$  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.

\*e-mail: thomas@ep1.rub.de



**Figure 1.** Drawing of the PANDA detector.



**Figure 2.** The PANDA target electromagnetic calorimeter: A barrel structure closed by two endcaps.

## 2 The Forward Endcap of the PANDA Calorimeter

In the forward endcap (Fig. 3) the crystals are mounted on a plane support disc (backplate). Through the center of the forward endcap the beam pipe is passing. The angular coverage therefore 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  $10^6 \text{ s}^{-1}$  for the innermost crystals. A corresponding radiation dose of up to 125 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 Submodules

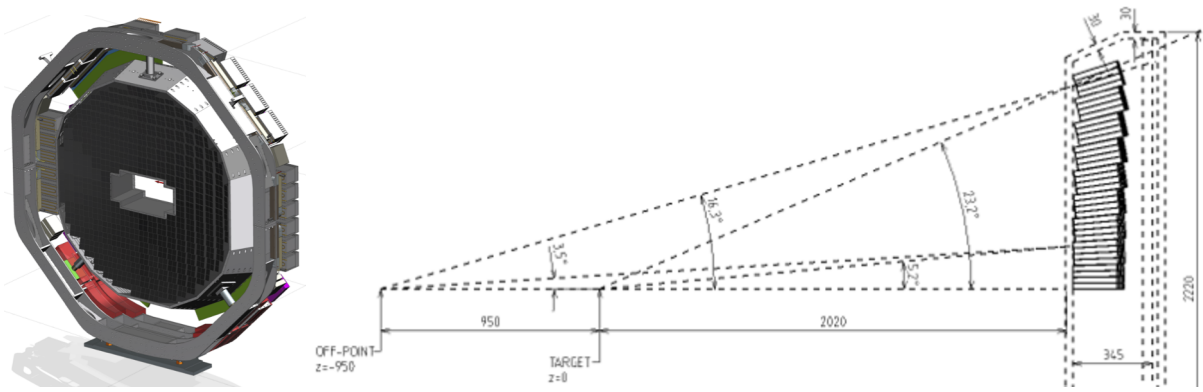
In the forward endcap the crystals are mounted in submodules of 16 or 8 crystals each combined in lightweight yet precise and stable carbon fibre aleveoles. Those are connected to the planar backplate by individual interface pieces providing the correct angle of slope with respect to the position in the forward endcap.

### 3.1 Photo Sensors

The very inner, high radiation exposed part of the forward endcap is equipped with vacuum photo tetrodes (VPTTs), 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  $200 \text{ mm}^2$ , the detector capacitance is about 22 pF. In the remaining part of the target spectrometer a pair of avalanche photo diodes (APDs), type Hamamatsu S11048, is used for readout. With a quantum efficiency of about 80%, active areas of  $100 \text{ mm}^2$ , 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.

### 3.2 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]. 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.



**Figure 3.** The forward endcap of the PANDA target electromagnetic calorimeter and its off-pointing geometry.

### 3.3 Crystal Units

Single crystals covered with reflective foil (DF2000MA by 3M [4]) and glued to a readout unit represent a crystal unit. The silicon adhesive Dowsil 3145 RTV was found to ensure a radiation hard optical transparent coupling withstanding 50 K of temperature difference between mounting and operation temperature.

### 3.4 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 crystals 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].

### 3.5 Temperature Sensors

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, which could be achieved during the beam tests at COSY/FZ Jülich. In order to allow for temperature measurements between the crystals, there is 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 carried out. Dedicated 64-channel 14-bit ADC readout boards have been developed.

## 4 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.

## 5 Monitoring System

A light pulser system 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 beam time. The LED pulser modules mimic the scintillation light pulses of lead tungstate 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. [9]

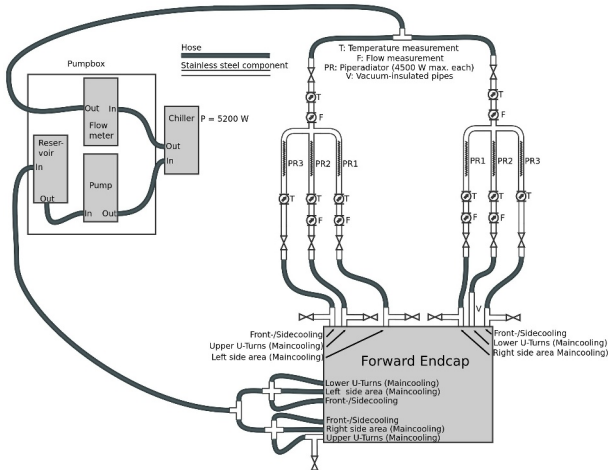
## 6 Cooling

Cooling is accomplished via bores in the aluminum backplate, aluminum cooling pipes running across the side walls, and by plastic hoses glued to the aluminum lid in front of the crystals. These lines carry a 1:1 methanol-water mixture supplied by a central cooling machine. Its reservoir temperature is chosen to be two 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. The complete cooling schema is given in Fig. 4.

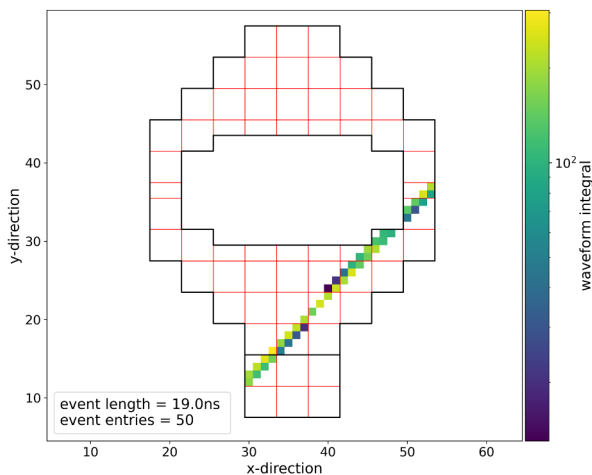
The entire cold volume is surrounded by aluminum plates thermally equalizing the boundary surfaces and electrically shielding the active detector volume. An isolation layer of vacuum insulation panels (VIPs) ensures the most effective thermal shielding possible in the given space for insulation material. Two layers of VIP panel tiles with overlaying joints minimizes thermal bridging.

## 7 COSY Beam Tests

In two beam weeks in August and September 2023 the forward endcap was tested with 2.5 GeV/c protons given to a 4 cm thick plastic target located 2 m in front of the detector.



**Figure 4.** Cooling scheme of the forward endcap.



**Figure 5.** Visualization of a cosmic muon traversing the forward endcap.

The PANDA experiment is designed to run a triggerless data acquisition (DAQ) system. However, this system was not yet available when the beam tests were carried out. Without a central trigger available either a constrained free-running DAQ system based on the existing DAQ of the Crystal Barrel experiment at ELSA, Bonn, was set up. External time marks were distributed across all SADCs allowing a synchronization of FPGA clocks and finally time-sorting of events. Fig. 5 basically demonstrates the functionality of the DAQ system by visualizing a cosmic muon track traversing the forward endcap.

Besides the full system setup and test of the general operation of the PANDA forward endcap at its target operation temperature the COSY beam tests were intended to perform a  $\pi^0/\eta$  calibration and derive calibration constants for all crystals mounted to the detector. After a rough single channel precalibration using minimum ionizing events a clear  $\pi^0$  peak with a mass resolution of 5 MeV/c<sup>2</sup> could already be derived from a subset of the data taken. This corresponds to a relative energy resolution of about 3.5 %

which is in good agreement with the targeted energy resolution of the PANDA forward endcap of

$$\frac{\sigma_E}{E} = \frac{2\%}{\sqrt{0.135}} + 1\% = 6.4\% \quad (1)$$

in the  $\pi^0$  invariant mass region considering a gain loss of the VPTTs in the magnetic field of the PANDA solenoid by a factor of about two compared to the setup used at COSY.

Work on a detailed energy calibration comprising the whole data taken is ongoing.

## Acknowledgments

We wish to thank the staff of the COSY (FZ Jülich) accelerator for their support and help during the forward endcap test beams and the preparation work before. We also thank the CMS collaboration for borrowing mounting tools for crystal submodule installation in Jülich.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093.

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