# The Electromagnetic Calorimetry of the PANDA Detector at FAIR

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**Abstract**. The PANDA collaboration at FAIR, Germany, will focus on undiscovered charm-meson states and glueballs in antiproton annihilations to study QCD phenomena in the non-perturbative regime. For fixed target experiments at the storage ring HESR a $4\pi$-detector for tracking, particle ID and calorimetry is under development and construction to operate at high annihilation rates up to 20 MHz. The electromagnetic calorimeters are composed of a target spectrometer (EMC) based on $PbWO_4$ crystals and a shashlyk-type sampling calorimeter at the most forward region. The EMC, comprising more than 15,000 crystals, is operated at a temperature of -25 ºC and read-out via large-area avalanche photo-diodes or vacuum photo-triodes/tetrodes. The photo sensor signals are continuously digitized by sampling ADCs. More than 50% of the high quality PWO-II crystals are delivered and tested. The excellent performance with respect to energy, time and position information was determined over a shower energy range from 10 MeV up to 15 GeV by operating several prototype detectors. In addition, the concept of stimulated recovery has been investigated to recover radiation damage on- and off-line during the calorimeter operation. Besides the overall concept of the target spectrometer the response function of the shashlyk spectrometer down to photon energies even below 100 MeV is presented.

## 1. The overall concept

Lead tungstate ($PbWO_4$ or PWO) has become a widely used scintillator material in medium and high energy physics [1,2,3] due to its compactness, fast response, short decay time and radiation hardness. For applications at medium energies the initially low luminescence yield has been significantly improved and optimized, leading to a second generation PWO-II [4], which was developed in collaboration with the *Bogoroditsk Technical-Chemical Plant* (BTCP), Bogoroditsk in Russia.

The PANDA detector, one of the approved major experiments at the future FAIR facility at GSI (Darmstadt, Germany), is dedicated to the hadron-physics program exploiting the stored and cooled beam of anti-protons. The research program is focusing on charmonium spectroscopy, gluonic excitations, open and hidden charm in nuclei and gamma-ray spectroscopy of hypernuclei [5]. Figure 1 provides an overview of the target and forward section of the PANDA detector and marks the two electromagnetic calorimeters EMC and FSC, respectively.

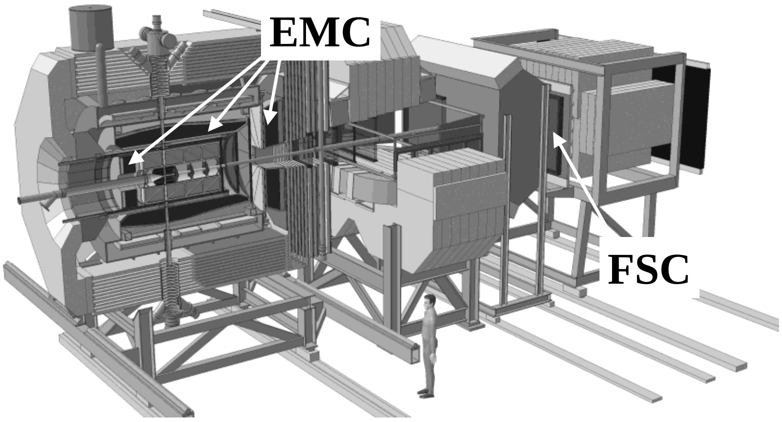


**Figure 1.** Schematic view of the PANDA detector consisting of a Target and Forward Spectrometer. The electromagnetic calorimeters consist of the EMC in the target and the FSC in the forward region, respectively.

## 2. The detector concept of the EMC in the target region

The electromagnetic calorimeter (EMC) of the target spectrometer has to provide high-resolution photon and meson spectroscopy [6,7]. It will have to cope with photons in the energy range starting at a few tens of MeV up to several GeVs. A pair of large area avalanche photo diodes (LAAPD) or a vacuum photo triode/tetrode (VPT, VPTT) are foreseen as photo-sensor of the individual crystal to allow operating in the magnetic field of the superconducting solenoid. Figure 2 illustrates two of the three major components of the calorimeter, the barrel and forward endcap. Irrespectively of the collected percentage of the light yield, additional cooling reduces the thermal quenching of the scintillation processes and allows an improvement of the energy resolution, when photon statistics dominates. A temperature of T = -25$^{o}$C as the operating temperature provides a light increase of a factor of ~ 4 compared to room temperature.

The quality of PWO was improved primarily due to a reduced concentration of defects achieved by raw material selection and growing technology. The co-doping with La- and Y-ions could be reduced to a level <40 ppm. Therefore, full size crystals of 200mm length and nearly rectangular shape deliver at least 16 photoelectrons per MeV measured at room temperature using a phototube with bialkali photocathode. The selection of the raw material has reduced those impurities leading to slow decay components. The response is dominated by the decay component of $\tau$ = 6.5ns.

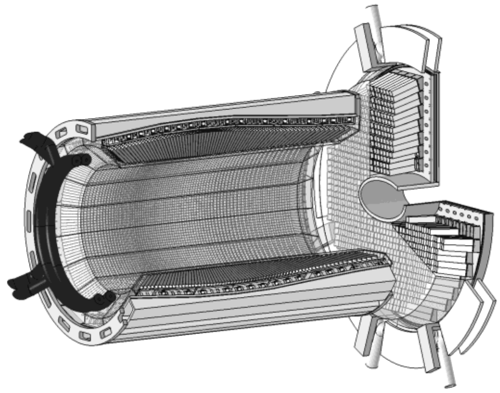

**Figure 2.** Schematic figure of the barrel and forward end cap as major components of the electromagnetic calorimeter of the PANDA target spectrometer (EMC).

The layout of the barrel comprises 16 identical slices. Each one consists of 710 tapered PWO crystals of 200mm length shaped in eleven geometries of two different symmetries. All crystals have a transversal size slightly above the Moliére radius of 2.1cm. The 11.360 crystals are pointing slightly off the asymmetrically located target position. Each crystal is contained in a carbon fiber alveole including the two rectangular LAAPDs (active area 7x14mm$^2$), the pre-amplification and shaping circuits. Low noise and power consumption and a dynamic range of 10,000 are achieved by a custom designed ASIC (*APFEL*). The concept of the front-end electronics is based on count rates of 100kHz per module and all components will be integrated into the cold section temperature stabilized on the level <0.1$^o$C. The mechanical support structure will house the electronics for control and digitization to minimize the space for signal transfer out of the detector.

Both endcaps are designed in a similar manner as illustrated in figure 2. However, crystals are of identical and slightly tapered (forward endcap) or straight (backward endcap) shape pointing off the target. In order to cope with count rates well above 500kHz vacuum photo triodes/tetrodes are chosen in the most forward region due to the momentum boost in a fixed target experiment.

## 3. The quality of PWO crystals

The so far available PWO crystals were produced by the Bogoroditsk Technical Chemical Plant, Bogoroditsk, in Russia. The mass production was performed with very selective quality limits for optical transmittance, homogeneity, light yield, scintillation kinetics and radiation hardness.

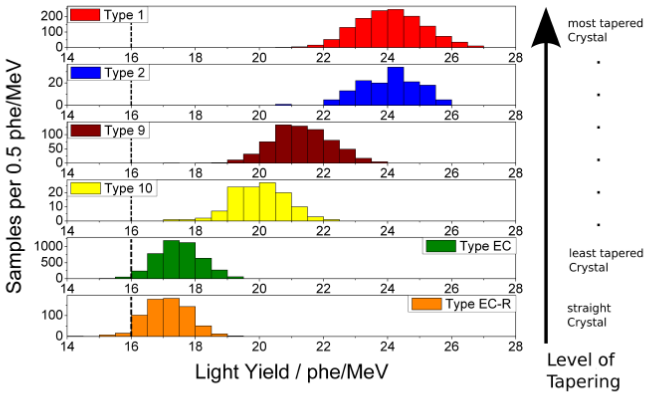


**Figure 3.** Distribution of the light yield for different crystal shapes ordered by the level of tapering.

The general acceptance tests were performed in close collaboration with the CMS/ECAL collaboration at CERN exploiting the ACCOS machine, which was adapted to the PANDA geometry and specifications. The measurements of radiation hardness and absolute light yield including cross checks at low temperature as well as the final analysis are done at Giessen. So far, more than 9.000 crystals have been delivered and are tested.

The optical transmissions at the relevant wavelengths of 360, 420 and 620nm, respectively, are measured longitudinally and perpendicularly to the crystal axis in order to control the homogeneity. The obtained values are well above the specification limits (T≥35% @ 360nm; T≥60% @ 420nm and ≥70% @ 620nm). The significantly improved light yield is documented in figure 3. The detected number of photoelectrons per MeV deposited energy (> 16 p.e./MeV) is determined at room temperature (T=18$^o$C) with a standard photomultiplier with fused silica window and bialkali photocathode. Light collection in a more tapered crystal shape further enhances the effective light yield compared to the nearly straight geometry of the endcap modules. More than 90% of the light is collected within a time gate of 100ns, which even holds when crystals are cooled down to T=-25$^o$C.

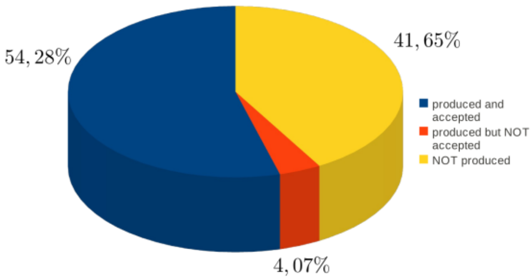


**Figure 4.** Present status on the crystal delivery for the PANDA EMC.

The most critical parameter is the change of the absorption coefficient Δk due to radiation damage. The crystals are irradiated at room temperature at the facility at Giessen with an integral dose of 30Gy using a set of $^{60}$Co sources (dose rate 4Gy/minute). The longitudinal transmission is measured up to a wavelength of 900nm delayed by 30 minutes after irradiation in order to exclude fast recovery processes. The required value $\Delta k \leq 1.1\text{m}^{-1}$ at 420nm guarantees that light losses due to radiation damage within an experimental period of 6 months remain tolerable even if the detectors are operated at low temperature. The rejection rate is on the level of ~5%. Figure 4 provides an overview of the delivered crystals. Unfortunately, BTCP went out of business recently. As an alternative manufacturer for the yet missing PWO crystals prototypes produced by SICCAS at Shanghai, China, are under investigations and fulfill presently most of the required specifications.

## 4. Prototype tests

In the past years several experiments with full size prototype arrays in PANDA geometry (tapered, 200mm length) have been performed to determine the response functions to photons and hadrons over a wide dynamic energy range [5, 7, 8]. The achievable energy resolution for electro-magnetic probes up to 15GeV energy is the most relevant parameter to enable the experimental program.

The tagged photon facilities at MAXLab (Lund, Sweden) and at MAMI (Mainz, Germany), respectively, have provided energy-marked photons between 20MeV and 1.5GeV with high intrinsic resolution. The measurements at a temperature of T=-25$^{o}$C were performed either using a photomultiplier tube at the lowest photon energies or a single LAAPD. The further amplification, digitization and data acquisition was done with commercial electronics.

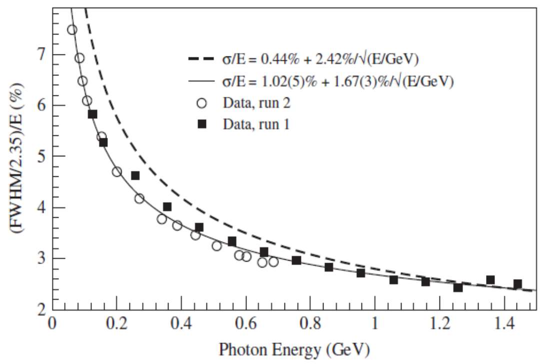


**Figure 5.** Cluster energy resolution as a function of the tagged photon energy obtained in two different measurements for a 3x3 matrix. The solid line is a fit to the data obtained after digitization in a sampling ADC. The dashed line corresponds to a fit to data converted with conventional readout electronics.

At photon energies as low as 20 MeV an excellent resolution σ/E<13% was achieved. The corresponding results up to 1.5GeV, as shown in figure 5, were obtained with a single LAAPD as photo-sensor. Exploring the upper energy limit figure 6 shows the line shape of a reconstructed shower created by 15 GeV positrons measured at CERN. Slightly depending on the point of impact, an energy resolution of σ/E<1.5% was derived. Even further improvements are expected by adding a second LAAPD, the preamplifier ASIC and performing digitization with a customized sampling ADC. Timing resolutions well below σ = 1ns for photon energies above 100MeV are confirmed already.

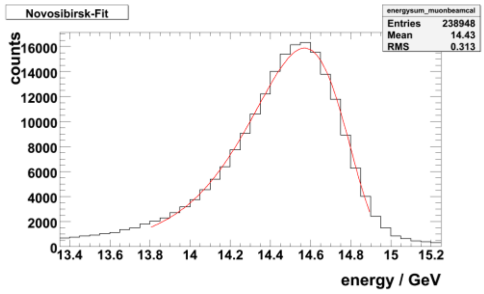


**Figure 6.** Line-shape of the response of a 5x5 PWO matrix (PROTO60) to the EM shower induced by 15GeV positrons of a CERN test beam. A 150GeV/c muon beam has been used for relative and absolute calibration.

## 5. Radiation damage and stimulated recovery

As investigated within the collaboration [9], the time constants of the recovery mechanisms become extremely slow at T=-25°C in the order of τ >400h. During irradiation the effective light yield deteriorates asymptotically towards a value depending on the radiation hardness as expressed by Δk. The inner part of the forward endcap will cope with a dose rate of 20mGy/h for the maximum event rate of $2{\cdot}10^7$ $p\bar{p}$- annihilations. If crystals with Δk<0.6m$^{-1}$ are selected, the detector module will lose <50% of the signal response. Color centers created during irradiation due to point structure defects or traps for electrons and holes cause absorption bands in a wide spectral region but can be spontaneously relaxed afterwards via thermo-activation. Therefore, heating of the crystal is the standard annealing procedure, which requires the disassembly of the detector system. Our R&D program for PWO-II has invented the process of *stimulated recovery* [10], which enhances significantly the recovery by illumination with external light even in the infrared region. Figure 7 illustrates the effect observed at room temperature after an irradiation with an integral dose of 30Gy. The recovery with illumination time is expressed by the change of the induced absorption coefficient Δk at 420nm using light of different wavelength.

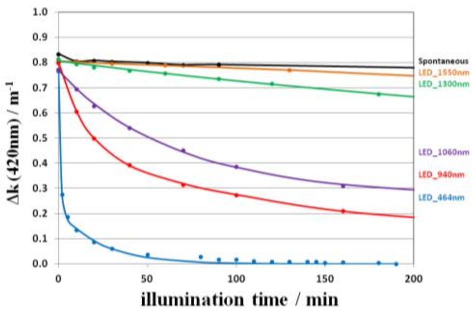


**Figure 7.** Recovery of a PWO-II crystal after irradiation with 30Gy at room temperature.

More relevant for the PANDA-EMC application is the behavior at low temperature. For blue light, nearly 90% of the original signal amplitude can be restored within the first 200 minutes imposing a photon flux of ~$10^{16}$ photons/s. Even at longer wavelength (~950nm) a significant recovery is observed with longer time constants and indicates sensitivity to different color centers. Depending on the wavelength sensitivity of the quantum efficiency of the different photo sensors, *stimulated recovery* can be applied on- or off-line without bringing the calorimeter up to room temperature.

## 6. The forward calorimeter FSC

In order to reach a nearly $4\pi$ detection efficiency for electromagnetic probes the forward solid angle determined by the forward spectrometer is covered by a sampling calorimeter of 4.6 $m^2$ surface comprising 54x28 cells of a shashlyk type design. Each sub-module has a cross section of 5.5x5.5$cm^2$ (~ $1R_M$) composed of 380 layers of lead absorbers (0.275mm thick) and plastic scintillator tiles (1.5mm thickness), respectively, with a total length of 68.4cm corresponding to 19.6 $X_o$. The scintillation light is collected and accumulated via 18 wavelength shifting fibers (Bicron BC91, $1mm^{\varnothing}$), which are inserted through holes and form loops on the front side of the module. Photomultipliers ($19mm^{\varnothing}$) are used as photo sensors since the calorimeter is placed at sufficient distance to the tracking magnets. Figure 8 illustrates the mechanical design of the two parts surrounding the beam pipe.

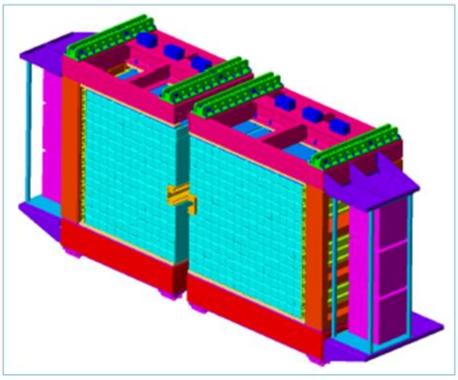

**Figure 8.** Schematic view of the forward shashlyk calorimeter comprising in total 54x28 detector cells arranged in two sections on both sides of the beam pipe.

The design of the shashlyk calorimeter is optimized for electromagnetic probes and a very low detection threshold to cover the full photon energy range down to a few tenths of MeV. Initial tests with electrons between 1 to 20 GeV, performed at the test beam facility at IHEP Protvino, provided first experience to optimize the detector structure, the overall performance with respect to energy, time and position response and the envisaged read-out chain including photo-sensors and signal digitization.

However, the most sensitive criteria to explore the detector limitations were performed recently using energy marked photons between 100MeV and 750MeV, respectively. The high-resolution photon beam was provided by the Bremsstrahlung tagging facility at the electron accelerator MAMI at Mainz in Germany.

Photomultiplier tubes of two different types (Philips XP1912, Hamamatsu R7899) were used as photo sensors and a sampling ADC (Wiener AVM16) was performed the digitization of the complete signal shape. All detector units composing a 6x6 matrix were relatively calibrated by impinging the direct photon beam of approximately 10mm diameter onto the center of each module. Acceptable energy, position ($\sigma$ < 2cm) and time resolutions ($\sigma \sim 100ps/\sqrt{E/GeV}$) have been obtained so far from the reconstruction of the electromagnetic shower. However, the energy response of the individual detector modules show a not acceptable dependence on the point of impact of the photons. Therefore, a significant modification of the detector design has been initiated and to submit the required final technical design report. Figure 9 shows as an example the obtained promising energy resolution for different module clusters, however for a fixed point of impact.

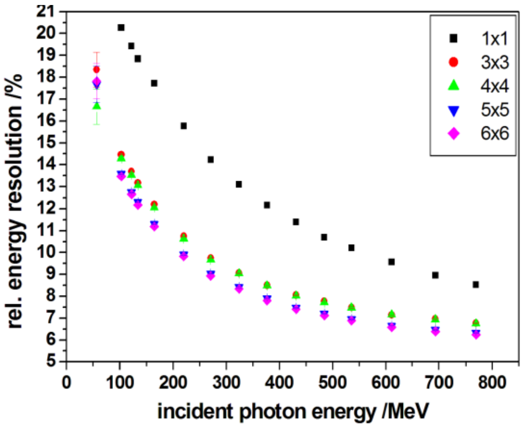


**Figure 9.** Energy resolution of a the shashlyk prototype measured with high-energy photons. The resolution of the reconstructed electromagnetic shower is shown for different clusters of modules. The beam was hitting the center of the central module.

## 7. Conclusions and outlook

The two high-resolution electromagnetic calorimeters, which represent one of the major detector components of the PANDA detector, will provide for the first time excellent performance over an extremely wide energy range as required by the physics program. The final construction of parts of the target EMC will be started soon in order to install the PANDA detector on time to be ready for commissioning in 2017/18.

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