Test of a Lead Tungstate-based Subunit
for the Electromagnetic Calorimeter
of the future PANDA Detector

Project Thesis by
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1 Introduction

The future PANDA (anti-Proton ANnihilation at DArmstadt) experiment will be located at FAIR in Darmstadt which is a future accelerator facility of the next generation. The commissioning of PANDA will be in 2012. An important part of the PANDA detector is the electromagnetic calorimeter (EMC) which will consist of 19’000 lead tungstate crystals. The EMC will be used to determine the energy and impact points of electrons, positrons and photons. Large Area Avalanche Photodiodes (LAAPDs) will be applied for the readout of the scintillator crystals.

In this report, a test measurement is presented that was performed to investigate on the behavior of a 3x3 lead tungstate crystal array with LAAPD readout. Both the experimental setup and the analysis of the data are shown. This experiment serves as a preliminary study to figure out the best material for the EMC of PANDA. In order to get a clue of the quality of the material, the energy resolution of the 3x3 array was extracted. Furthermore, simulation data is illustrated to compare with the experiment.

But firstly, the reader will be introduced to the background of the PANDA experiment and the envisaged physics program. Afterwards, the theory of electromagnetic calorimeters will be treated as well as the properties of the PANDA EMC. The reader will also be guided through the background of the lead tungstate crystals and the LAAPDs. The measurement in Mainz will be presented in chapter 5 and the analysis of the experiment in chapter 6.
2 The future PANDA Experiment

2.1 Location

The PANDA (anti-Proton ANnihilation at DArmstadt) experiment is a future project of the GSI (Gesellschaft für Schwerionenforschung) in Darmstadt. It will take place at FAIR (Facility of Antiproton and Ion Research) which will be an international accelerator facility of the next generation. FAIR is going to be located at the site of the existing GSI laboratory. It will consist of a double ring facility with a circumference of 1100 meters, a system of cooler-storage rings for effective beam cooling at high energies and various experimental halls. The existing GSI accelerators will be used as injectors for the new facility. The double ring synchrotron will be able to provide ion beams of unprecedented intensities. Intense secondary beams of unstable nuclei or antiprotons can be produced. The system of storage-cooler rings allows to improve the quality of the secondary beams. The High Energy Storage Ring (HESR) for antiprotons will perform stochastic and electron cooling and will provide $5 \times 10^{10}$ stored antiprotons at beam momenta of 1 to 15 GeV/c. The PANDA detector will be an internal experiment at HESR. Figure 1 shows a schematic view of the GSI and FAIR area with HESR and the PANDA hall in red.

![Schematic view of the GSI and FAIR area with HESR and the PANDA hall in red](image)

Figure 1: Schematic view of the existing and future GSI and FAIR facilities (with the PANDA hall in red) [1].
2.2 The envisaged Physics Program

Antiproton beams with unequaled intensity and quality (in the energy range 1-15 GeV/c) as provided by FAIR are an excellent tool to investigate fundamental questions. These kind of antiproton beams allow access to strange and charm quarks and to substantial production of gluons. The physics program of the PANDA experiment focuses on charmonium spectroscopy and the search for hybrids and glueballs. But a large variety of other physics topics are planned at PANDA, such as hypernuclear physics or investigations into the structure of the proton. The following experiments are proposed (selection):

- Charmonium spectroscopy: Precision measurements of mass, width and decay branches of all charmonium states, with a view to gain information about the quark-confining potential.
- Gluonic excitations (Glueballs and Hybrids): Determination of the gluonic excitations (in the charmonium mass range 3-5 GeV/c^2) which have been predicted by QCD.
- Hypernuclei: Precision γ-ray spectroscopy of single and double hypernuclei.
- Proton structure: Measurement of timelike form factors with high precisions over a wide kinematical range.

All these experiments together shall enable a deeper understanding of the structure of hadronic matter in all its forms and of how the world is built by leptons and quarks.

2.3 The PANDA Detector

The envisaged physics program demands a challenging amount of requirements of the detector. These requirements can be summarized as follows:

- full angular coverage for charged as well as neutral particles
- particle identification in a wide range of particles (for instance γ-rays, leptons, muons, kaons) and energies
- high energy and angular resolution for charged and neutral particles
- high rate compatibility

Basically, the concept of the detector is a shell-like arrangement of various detector systems surrounding the interaction point. The detector is divided into two spectrometers: a target spectrometer (TS) that surrounds
2.3 The PANDA Detector

the interaction region and a forward spectrometer (FS). The combination
of these two spectrometers provides a full angular coverage and takes into
account the wide range of energies. Figure 2 shows an overview of the
PANDA detector with the individual subunits. The antiproton beam will
interact with the target at the cross point which is located inside a large
superconducting solenoid.

Particles emitted with laboratory polar angles larger than 10° are only
measured with the TS. A silicon micro-vertex detector (MVD) will surround
the interaction volume. Moreover, a second tracking detector will be situated
starting from a radial distance of 15 cm from the beam line up to 42
cm. Particle identification with a ring-imaging Cherenkov (RICH) counter
follows at a radial distance of 45 cm. The RICH counter will be realized
by the detector of internally reflected Cherenkov light (DIRC). Two sets of
mini drift chambers (MDC) and another Cherenkov detector will cover the
forward region. The inner detectors are surrounded by an electromagnetic
calorimeter (EMC). The EMC will consist of about 19'000 crystals with
avalanche photodiode (APD) readout. Scintillating bars for muon identifi-
cation will also be mounted.

Particles emitted with polar angles below 10° in the horizontal and 5°
in the vertical direction are detected with the FS. The current design plans
a 1 m gap dipole and tracking detectors for a momentum analysis of the
charged particles. Photons will be detected by a calorimeter made up of lead-
scintillator sandwiches. Other neutral and charged particles with momenta
close to the beam momentum will be detected in the hadron calorimeter and
muon counters.
Of special interest for this task is the electromagnetic calorimeter which will be explained in detail in the next section.
3 General Principles of an Electromagnetic Calorimeter

3.1 Introduction

Electromagnetic calorimeters (EMCs) are used to determine the energy and impact points of electrons, positrons and photons with energies above a few 10 MeV [3]. Thereby these particles generate cascades of secondary particles through successive bremsstrahlung and pair production inside the calorimeter material. The secondary particles themselves provide a measurable ionization or light signal.

EMCs can be built either as homogenous devices or as sampling calorimeters which are composed of alternate absorbing and detecting layers. A homogenous calorimeter is at the same time detector and shower material. It reaches ideal resolution by consisting of liquid noble gases or high density and fast scintillating crystals.

The electromagnetic calorimeter of PANDA is proposed to be constructed of scintillating lead tungstate (PbWO$_4$) crystals covering all showers. Therefore, it will be a homogenous calorimeter [4]. The crystals will be arranged very close for detecting the full energy of the cascade caused by one incoming photon. Lead tungstate is an inorganic crystal that is doped with activator-centers. Incoming ionizing particles produce free electrons, free holes or electron-hole pairs (excitons) in this material. These excited states come upon the activator-centers whereon the centers become excited as well. After that, the activator-centers decay into the ground state again under emission of photons with visible wavelength. The produced light is afterwards converted into electrical signals using either photo multipliers or avalanche photodiodes as in the case of PANDA.

The energy resolution of an electromagnetic calorimeter depends on the energy of the incident particle as follows:

$$\sigma_E \approx a\sqrt{E} + b + c$$

$E$ is the energy of the incident particle, $\sigma$ is the standard deviation of the energy measurement and $a$, $b$ and $c$ are constants depending on the detector type.

3.2 Bremsstrahlung

The electromagnetic shower is generated by high-energy electrons or photons which loose energy due to bremsstrahlung. Bremsstrahlung occurs when charged particles are accelerated or slowed down by the electric field of nuclei in matter, whereupon photons are emitted. The following equation describes the amount of energy lost in bremsstrahlung:
3.3 Electromagnetic Shower

\[
\frac{dE}{dx} = \frac{E}{X_0}
\]  

(2)

\(dE/dx\) is the lost energy, \(E\) is the energy of the particle and \(X_0\) is the so-called radiation length. The radiation length can be described as the distance over which the energy of an incoming electron decreases by a factor of \(e\) (Euler constant) because of bremsstrahlung-processes. For a photon, this distance corresponds to the distance over which there is an approximate probability of 54% to perform pair production. The radiation length can be approximated as follows:

\[
\frac{1}{X_0} \approx 4 \left( \frac{1}{m c} \right)^2 \frac{Z(Z + 1) \alpha^3 n_\alpha}{\ln 183} \frac{183}{Z^3}
\]

(3)

In this equation, \(m\) is the mass of the electron, \(c\) the speed of light, \(\hbar\) is the Planck’s constant divided by \(2\pi\), \(Z\) is the atomic number, \(\alpha\) is the coupling constant and \(n_\alpha\) is the number of atoms per cm\(^3\). Materials with high \(Z\) values have a short radiation length which can reduce the calorimeter depth and the dimensions of the detector. An electromagnetic calorimeter needs to have a length of about 15 - 25 \(X_0\), so that the electromagnetic shower is totally absorbed in the material.

### 3.3 Electromagnetic Shower

If the incoming photons holds high energy, it is possible that pair production occurs. In this process the photon converts into an electron-positron pair. The electron and also the positron underlie bremsstrahlung and are therefore deflected. A photon is emitted which again can produce an electron-positron pair if the energy is high enough. The shower process spreads in all directions, but mainly in the longitudinal one. Figure 3 illustrates the proceeding of such a cascade. At this, the energy of the incoming photon is \(E_0\) and on the \(x\)-axis the radiation length is sketched.

The shower continues until the critical energy \(E_c\) is reached. \(E_c\) is an electron energy at which the cross section of bremsstrahlung becomes similar to that of pure ionization [5]. Therefore, the shower is stopped and no further secondary particles are produced. The equation below shows that the critical energy depends on the atomic number \(Z\) of the detector material:

\[
E_c \approx \frac{550 MeV}{Z}
\]

(4)

It is obvious that a material with a high \(Z\) value corresponds to a low critical energy.

At energies below a few MeV, Compton effect and the photoelectric effect become dominant. In Compton effect the photon scatters off an atomic electron. Whereas in the photoelectric effect the photon is totally absorbed by
3.3 Electromagnetic Shower

![Diagram of an electromagnetic shower]

Figure 3: Illustration of an electromagnetic shower with initial energy $E_0$ [6].

the material and an electron carrying its energy is emitted. Both processes represent collisions with the atomic electrons and cause ionization of the detector material. Concerning the conducted test measurement in Mainz, pair production was the dominant process for the incoming high energy photons.

In this context the Moliere radius should also be mentioned. It is a characteristic constant of a calorimeter material and is related to the radiation length:

$$R_M = 0.0265X_0(Z + 1.2)$$

(5)

$X_0$ is the radiation length and $Z$ is the atomic number of the material. The Moliere radius $R_M$ is a good scaling variable for describing the transverse dimension of an electromagnetic shower.
4 The Electromagnetic Calorimeter of the PANDA Detector

4.1 Layout

The electromagnetic calorimeter of PANDA will consist of about 19,000 lead tungstate (PbWO$_4$) crystals. There will be four different parts: the forward endcap, the backward endcap, the forward spectrometer and the barrel. Figure 4 displays the three central parts of the EMC. The barrel is seen in the middle, the forward and backward endcaps are shown on the left and right of the picture. The dimension is also illustrated. The entire arrangement will have a length of approximately four meters. It will be possible to achieve almost a coverage of $4\pi$ for multiphoton and multiple meson detection due to this special layout. The forward spectrometer is located 7 meters downstream the target and will have an area of about 3m$^2$. It is not presented in figure 4.

![Figure 4: Schematic layout of the EMC of PANDA [7].](image)

The final geometry of the crystals and the total number of modules has not been fixed yet. The length of one single crystal will be about 20 $X_0$. A final design study based on beam tests and simulations will define the architecture.

4.2 PbWO$_4$ crystals

Lead tungstate-based crystals have some very attractive features. They are fast scintillating crystals with a short decay time, they have a short radiation length of about 0.9 cm, a Moliere radius of 2.2 cm and a low critical energy. Because of the short radiation length the detector can be built very compact and a lot of money will be saved.

On the other side, the luminescence yield is badly low, only approximately 1% of NaI(Tl) crystals. However, it can be increased by operating
4.3 Avalanche Photodiodes

the crystals below room temperature due to thermal quenching. Some of the relevant parameters of PWO (PbWO$_4$) are given in table 1. Figure 5 shows two lead tungstate elements as they have been used for the test measurement in Mainz.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PWO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8.28 g/cm$^3$</td>
</tr>
<tr>
<td>Melting Point</td>
<td>1123 $^\circ$C</td>
</tr>
<tr>
<td>Radiation Length</td>
<td>0.89 cm</td>
</tr>
<tr>
<td>Moliere Radius</td>
<td>2.0 cm</td>
</tr>
<tr>
<td>Luminescence</td>
<td>420 nm</td>
</tr>
<tr>
<td>Decay Time</td>
<td>5-15 ns</td>
</tr>
<tr>
<td>Relative Light Output compared to NaI(Tl)</td>
<td>1 %</td>
</tr>
</tbody>
</table>

Table 1: Some properties of PWO [2].

Figure 5: Two PWO elements, each with size 20x20x200 mm$^3$ [2].

A few years ago, a research program has been started to improve the crystal quality and to launch the technology for mass production. In the course of this, the primary crystals were doped simultaneously with La (Lanthanum) and Y (Yttrium) ions. As a result of this development, the scintillation light yield could be increased by 80% and the doped crystals contained twice less Frenkel type defects [8]. These modified crystals are called PWO-II and will most likely be used in the PANDA detector.

4.3 Avalanche Photodiodes

4.3.1 Basic Theory

The operation of the electromagnetic calorimeter in the magnetic field of the solenoid excludes the use of conventional photomultiplier tubes for the
readout of the PWO-II crystals. For that reason, a photo sensor insensitive to magnetic fields is necessary. Moreover, an internal gain of the photo sensor is needed, because of the low light yield of lead tungstate. Silicon avalanche photodiodes (APDs) satisfy these requirements and are therefore an ideal solution for the calorimeter of PANDA.

When a photon enters a photodiode, an electron-hole pair is generated if the energy of the incident photon is higher than the band gap energy. The band gap of silicon is 1.12 eV at room temperature, whereby it becomes sensitive to wavelengths shorter than 1100 nm. Two terms needed to describe this sensitivity are called photosensitivity $S$ and quantum efficiency $QE$. $S$ is given by the photocurrent divided by the incident radiant power (A/W) and $QE$ is the ratio of electron-hole pairs generated versus the number of incident photons (%). The following relation connects these two terms:

$$QE = \frac{S \times 1240}{\lambda} \times 100\%$$  

(6)

$\lambda$ is the wavelength of the incoming photon. Figure 6 shows a schematic view of a silicon APD with reverse structure. The photons enter the APD via the $p^{++}$ layer. They are absorbed in the $p^+$ layer where the electron-hole pairs are generated. Due to the electric field, the electrons drift towards the $n^{++}$ side and the holes towards the $p^{++}$ side. If the electric field is sufficiently high, these charge carriers will likely collide with the crystal lattice whereon ionization takes place. Due to the ionization process, new electron-hole pairs are generated. These electron-hole pairs again create additional pairs. A chain reaction occurs which is called avalanche multiplication. The avalanche multiplication starts when the electric field reaches a strength of about $2 \times 10^5$ V/cm [9]. The charge collection of all the produced electrons takes place in the $n^{++}$ region. A passivation layer made of silicon nitride ($Si_3N_4$) is mounted in front of the $p^{++}$ layer for reducing the decrease of quantum efficiency caused by reflection losses.

![Figure 6: Schematic view of an APD with reversed structure [2].](image)

The internal current gain of an APD becomes higher, when the applied
4.3 Avalanche Photodiodes

Reverse voltage increases as well. There are various expressions for the multiplication factor of an APD. An informative equation is given below:

\[ M = \frac{1}{1 - \int_{0}^{L} \alpha(x) dx} \]  

(7)

\( L \) is the space charge boundary for electrons and \( \alpha \) is the multiplication coefficient for electrons (and holes). \( \alpha \) has a strong dependence on the applied field strength, doping profile and temperature [10].

An important noise factor is the excess noise which describes the statistical noise that is inherent with the stochastic multiplication process. It is denoted by \( F(M) \) and can be expressed as:

\[ F = \kappa M + \left( 2 - \frac{1}{M} \right) (1 - \kappa) \]  

(8)

\( \kappa \) is the ratio of the hole impact ionization rate to that of electrons. \( F(M) \) is one of the main factors which limit the best possible energy resolution achievable.

4.3.2 Large Area Avalanche Photodiodes

APDs for the readout of PWO crystals have already been developed for another experiment: CMS (Compact Muon Solenoid) at CERN. These APDs have several advantages: compactness with an overall thickness of about 200 \( \mu \)m, low cost, insensitivity to magnetic fields and a high quantum efficiency of approximately 70%. A large disadvantage of these APDs is their relatively small active area of 5 x 5 mm\(^2\) compared to the area of the crystal endfaces. For that reason, the development of large area avalanche photodiodes (LAAPDs) with an active area of 10 x 10 mm\(^2\) was initiated [11]. The LAAPDs for PANDA will have the same internal structure as the APDs for CMS (see Figure 6). There will be two LAAPDs for detecting the scintillation light of one crystal. Figure 7 shows a picture of two standard APDs and one LAAPD to compare the different sizes of the active areas.

![Figure 7: Picture of two standard APDs and one LAAPD [12].](image)
The crystals used for the test measurement in Mainz have an endface area of 4 cm$^2$. For a measurement at $-25^\circ$C, there should be 450 impinging photons per MeV and 4 cm$^2$ area. The applied LAAPDs have a quantum efficiency of 70% and cover 2 cm$^2$. Therefore, the measurement should achieve 158 electron-hole pairs per MeV and 2 cm$^2$ in silicon.
5 Test Measurement at MAMI in Mainz

5.1 Preparation

The test measurement was performed at MAMI (Mainz Microtron) in Germany from 21st to 23rd of March 2007. MAMI is an electron beam facility that has recently been upgraded and delivers now electrons with energy up to 1.5 GeV. It was planned to use a 5 x 5 PWO-II array as crystal setup with LAAPD readout for the experiment. The preparation of the crystal array was conducted in Giessen, Germany. There the crystals were individually wrapped into Teflon foil and the LAAPDs were attached to the endface of the crystals with optical grease. The accomplished array was afterwards put into a temperature control box which is connected to a refrigerator. The refrigerator allows a cooling of the whole box down to $-25^\circ$C. The temperature control box was mounted on a table that can be moved by remote control both horizontally and vertically to direct the electron beam into any of the crystal elements. The entire arrangement was transported from Giessen to Mainz where it was reinstalled in the A2 measurement hall in front of crystal ball and TAPS (Two Arms Photon Spectrometer).

5.2 Experimental Setup

All crystal elements have the size 2 x 2 x 20 cm$^3$ and look therefore cuboid-like. Figure 8 shows a schematic view of the dimension of one crystal.

![Figure 8: Schematic view of the dimension of one crystal element.](image)

In total 25 PWO-II crystals were arranged as a 5x5 array. Four crystals have been produced by SICCAS (Shanghai Institute of Ceramics of the Chinese Academy of Science) in China and were put in the corners of the array. The remaining 21 elements came from BTCP (Bogoroditsk Technical Chemical Plant) in Russia. The LAAPDs were delivered by Hamamatsu Photonics in Japan. Two of them were used for the readout of one crystal. Actually there should have been a measurement of the full 5x5 array, but because of problems during the beam time only a 3x3 array could be measured completely. Figure 9 shows this 3x3 array inside the 5x5 matrix (light blue). Please notice the numbers of the elements of the light blue array, they will be used in the following.

Figure 10 shows the overall experimental setup at MAMI. The necessary
electron beam for this experiment is delivered by MAMI. When the electrons from the beam hit the Nickel radiator, bremsstrahlung occurs and the electrons emit photons. A dipole magnet generates a strong magnetic field whereon the electrons are deflected. The higher the energy of the electrons, the less they bend. For different values of the energy, there are different focal points which are located along a plane called focal plane. A ladder of 352 small plastic scintillators is placed in the focal plane [13]. The exact photon energy can be determined by recording the responding tagger module in coincidence with the bremsstrahlung photon observed in the test detector. Thereby a typical uncertainty of about 1-2 MeV arises. In this test measurement 16 different energies of the tagged photons were selected. They are illustrated in table 2.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.87</td>
<td>9</td>
<td>202.62</td>
</tr>
<tr>
<td>2</td>
<td>52.03</td>
<td>10</td>
<td>252.99</td>
</tr>
<tr>
<td>3</td>
<td>59.20</td>
<td>11</td>
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<tr>
<td>4</td>
<td>73.05</td>
<td>12</td>
<td>377.70</td>
</tr>
<tr>
<td>5</td>
<td>91.60</td>
<td>13</td>
<td>450.51</td>
</tr>
<tr>
<td>6</td>
<td>110.27</td>
<td>14</td>
<td>522.94</td>
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<td>7</td>
<td>133.75</td>
<td>15</td>
<td>601.48</td>
</tr>
<tr>
<td>8</td>
<td>150.28</td>
<td>16</td>
<td>674.52</td>
</tr>
</tbody>
</table>

Table 2: The 16 selected energies of the tagged photons.

Due to the table with remote control, the beam can be directed towards any crystal. When the photon beam is brought into a line with one crystal, the photons initiate an electromagnetic shower that spreads over the surrounding modules. The energy deposit in the neighboring crystals depend on the photon energy and can be reduced due to dead material (for example Teflon foil) between the crystals. Figure 11 shows two pictures. On the left side, one can see the temperature control box and the two tubes leading to the refrigerator. On the right side, the view into the cooled box is illustrated.
5.2 Experimental Setup

In front of the crystal array a fast plastic scintillator was mounted. It served as a charged particle veto to identify electrons or positrons that have been created by bremsstrahlung photons in the air. A new preamplifier was developed for amplifying the low level signal of the LAAPDs. For every LAAPD one preamplifier was used. The LAAPDs were supplied with high voltage (HV). The output signal of the preamplifier was split to serve a timing and an analog circuit. The timing signal continued to a constant fraction discriminator (CFD) to generate a timing reference. A CFD gives an output if the input signal is above a certain level, whereas the time of this output does not depend on the amplitude for a given rise time of the input signal. Both signals from the timing and the analog circuit were delayed passively by long coaxial cables till reaching the data acquisition system. There, an energy response was generated in a peak-sensing ADC (Analog to Digital Converter).

In general, two logic OR-units were used. The selected 16 tagger channels were fed into an OR and the signals of the crystal modules were as well directed into a logic OR. The event condition requires a coincidence between the tagger-OR and the trigger signal of the crystal element to be tested. The energy and time information of each scintillator together with the timing response of the relevant tagger channels were recorded event-by-event.

The measurement was performed at 0°C. The program of this experiment included the relative calibration as well as the final response measure-
5.2 Experimental Setup

Figure 11: Left: the temperature control box and the two tubes leading to the refrigerator. Right: View into the cooled box.

ment of the scintillator array. Due to problems, the relative calibration of an earlier experiment with a 3x3 array was utilized. Nevertheless, a long data run with the beam hitting the central detector could be performed to measure the shower distribution. The aim of the test measurement was to reconstruct the shower distribution and to extract the energy resolution of the crystal array.
6 Analysis of the Test Measurement

6.1 Relative Calibration

First of all, a relative calibration had to be done to ensure that a certain channel number in one crystal corresponds to the same channel number in all other crystals. In the course of this, the so-called pedestal values had to be determined. The pedestal is the channel number in the raw energy spectrum that corresponds to a photon energy equal to zero. It is normally the first channel number different from zero in the raw spectra and it should be identical for every tagger channel in one crystal.

During the test measurement in Mainz the beam was directed into the central crystal (number 13) of the 3x3 array. The data from the eight surrounding crystals was simultaneously recorded. The total energy spectrum of the central crystal shows 16 peaks, one for each tagger channel. The eight spectra from the neighboring crystals contain only low energy deposit according to the part of the electromagnetic shower reaching these crystals. The same patterns are valid for the beam being centered to one of the other crystals. There is one exception: only eight tagger channels were used because of the problems during the measurement (see chapter 5.2). In the calibration process, the position of all peaks had to be determined. On that account, each peak was fitted with a Matulevich fit function. This fit function can be described as follows:

\[
\begin{align*}
\text{for } E \geq E_p & : \quad y = G \\
\text{for } E \leq E_p & : \quad y = G + \exp \left[ \frac{E - E_p}{\lambda} \right] (1 - G)
\end{align*}
\]

with \( G = \exp \left[ -\frac{4\ln 2 (E - E_p)^2}{\theta^2} \right] \)  

\( E_p \) is the peak position of the response function, \( \theta \) specifies the FWHM (Full Width at Half Maximum) of the Gauss function and \( \lambda \) gives information on the asymmetry of the peak. Figure 12 illustrates one performed fit of crystal number 19 and tagger energy three.

<table>
<thead>
<tr>
<th>Crystal No.</th>
<th>Calibration Factor</th>
<th>Crystal No.</th>
<th>Calibration Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.49</td>
<td>14</td>
<td>0.47</td>
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<tr>
<td>13</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Calibration factor for each crystal.
6.1 Relative Calibration

By comparing the eight peak positions (with pedestals substracted) of one surrounding crystal to the corresponding ones of the central crystal, eight calibration factors can be extracted. These calibration factors should be identical within statistical errors. The mean value can be used as a normalization factor for the relative calibration. Figure 13 shows the eight calibration factors for crystal eight. Table 3 illustrates the mean value of the calibration factors for each crystal.

Figure 12: One performed fit for determining the peak position.

Figure 13: Calibration factors for crystal eight (extracted relative to crystal 13).
Figure 14: Reconstruction of the electromagnetic shower for two different tagger energies.

Because of the relative calibration, the reconstruction of the electromagnetic shower became possible. Figure 14 displays the distribution of the shower for two tagger energies: the lowest and the highest one. It is shown that most of the energy is deposited in the central unit [14]. One might re-
alize that the distribution is not a 100\% symmetric. This property probably occurs because the beam was not exactly focused on the center of crystal 13.

Figure 15: Illustration of the sum of all nine crystals, the sum of the eight surrounding crystals and the spectrum of the central crystal for two tagger energies.

For the calculation of the energy resolution it is necessary to generate the sum of the signals of all crystals for one tagger energy (for the beam
being directed to the central crystal). This is done by adding the energy contribution from the surrounding crystals event-wise to the spectrum of the central crystal. This means that for each event the amount of energy deposited in crystal element 7, 8, and so on has to be identified. The relative calibration enables this proceeding. Figure 15 shows the energy response for two tagger energies. In each case the sum of all nine crystals, the sum of the eight surrounding crystals and the spectrum of the central crystal are illustrated. The beam was directed to the central element.

![Figure 15: Energy response for two tagger energies.](image)

For the sum of all nine crystals, the peak positions were fitted as well. They are presented in figure 16 together with the peak positions from the central detector (pedestals are subtracted). The different peak positions are

![Figure 16: Peak positions of the central crystal and the sum of the 3x3 array plotted relatively to the beam energy.](image)

![Figure 17: Analogous to Figure 16 for crystal number eight.](image)
6.2 Energy Resolution

Plotted relatively to the beam energy. One might notice that there is linear relationship between the peak locations and the beam energy. This is an important test to check if the energy response follows a linear dependence. For all other crystals a linear connection could also be detected. Figure 17 shows the relationship for crystal number eight. It is not perfectly linear for element eight, but there is only a very small divergence from the linear function.

6.2 Energy Resolution

The energy resolution depends on the energy of the incident photon. It can be described by equation (1). One has to use the fitted peak positions (minus the pedestals) of the sum of all nine crystals to attain the energy resolution of the 3x3 array. The fitted peak positions (minus pedestals) stand for the energy. The $\sigma$ is given by the FWHM (Full Width at Half Maximum) of the energy peaks divided by 2.355. Therefore, the corresponding $\sigma$ divided by the fitted peak location minus pedestal times 100% results in the correct energy resolution in percent for the according beam energy.

\[
\frac{\sigma}{E} = 0.13\% + \frac{2.63\%}{\sqrt{E}} - 0.28\%
\]

![Energy Resolution of the 3x3 Array](Image)

Figure 18: Energy resolution of the 3x3 array as a function of the beam energy.
Figure 18 presents the obtained energy resolution of the whole array related to the beam energy. A fit function analogous to equation (1) was used. The function displayed in figure 18 was received as energy resolution. The energy resolution at 1 GeV could be extrapolated due to the fit function. It is illustrated as well in the figure.

6.3 Relative Energy Deposit

Figure 19 shows the relative energy deposit in the surrounding crystals. The fitted peak positions of the sum of the surrounding crystals were divided by the fitted peak positions of the sum of all nine crystals. The ratio is displayed as a function of the beam energy. One can recognize that the ratio becomes higher if the beam energy gets higher as well. At the lowest beam energy, there are about 7% deposited in the neighboring crystals. 20% are stored in the ring for the highest incident energy.

![Relative Energy Deposit in the Surrounding Crystals](image)

Figure 19: The relative energy deposit in the surrounding crystals.

6.4 Comparison with Simulation Data

In the following, figures from preliminary results of a simulation with GEANT 4 are displayed. They are compared to figures from the experimental data. Because of the simulation, an absolute energy calibration became possible and the real energy is shown.

In figure 20 one can see the distribution of the electromagnetic shower for beam energy equal to 450 MeV. Figure 21 shows the three peaks for
beam energy 450 MeV. The final figure 22 illustrates the energy resolution for the experimental and the simulation data. Although the data from the simulation is still preliminary, there is an extreme agreement between the experiment and the simulation performed with GEANT 4.

Figure 20: Distribution of the electromagnetic shower; data from simulation on top, experimental data below [15].
6.4 Comparison with Simulation Data

Figure 21: The sum of all nine crystals, the sum of the surrounding crystals and the spectrum of the central crystal for beam energy 450 MeV. Left: experimental data. Right: data from simulation [15].

Figure 22: The energy resolution of the 3x3 array: simulation and experiment in comparison.
6.5 Conclusion

Even tough the experiment had to be performed at 0°C and there were some problems during the beam time, the test measurement delivered good results. A nearly perfect linear relationship was found between the fitted peak positions (with pedestals subtracted) of each crystal and the beam energy. Moreover, the calibration relative to the central detector could be performed trouble-free. In the end, a good energy resolution of 2.22% at 1 GeV resulted. In an earlier experiment (performed with photomultipliers and a 5x5 PWO-II array) an energy resolution of 2.19% at 1 GeV was obtained. This older measurement was conducted at −25°C. The comparison of the two results show that the choice of LAAPDs for the readout of the electromagnetic calorimeter seems to be ideal. Nevertheless, the experiment should be repeated with the whole 5x5 array and at a temperature of −25°C. A better comparison between photomultipliers and LAAPDs then would become possible. In the future there will be test measurements with larger arrays. It is necessary to enlarge the size of the test array since the EMC of PANDA will contain about 19000 crystal elements.

The preliminary results from the simulation performed with GEANT 4 shows excellent results. The data from the simulation and the experiment coincide well and no better accordance could have been expected.
7 Summary and Outlook

The PANDA experiment is a future project of the GSI facility in Darmstadt. It will take place at FAIR which is an international accelerator facility located at the existing GSI site. The PANDA detector will be an internal experiment at HESR which will deliver antiprotons for the measurements. The physics program of PANDA will focus on charmonium spectroscopy and the search for hybrids and glueballs. As well, a large variety of other experimental topics are planned, for example the measurement of the timelike form factors of the proton. The commissioning of PANDA is planned in 2012.

An important part of the PANDA detector is the electromagnetic calorimeter (EMC). EMCs are used to determine the energy and impact points of photons, electrons and positrons. The EMC of PANDA will consist of about 19’000 PWO-II crystals with LAAPD readout. PWO-II (lead tungstate) is an inorganic and homogenous scintillator material. In the scintillator material, the incident particles generate cascades of secondary particles through successive bremsstrahlung and pair production. The secondary particles provide a measurable light signal which is converted into an electrical signal by the LAAPDs (Large Area Avalanche Photodiodes).

A test measurement with a 3x3 PWO-II crystal array was conducted at MAMI in Mainz. Two LAAPDs per crystal were used. The electron beam of MAMI was utilized to generate a photon beam (via bremsstrahlung processes) which was directed to one of the crystals. The crystal array and the LAAPDs were located in a temperature control box. They were cooled down to 0°C to improve the light yield of the crystals. The aim of the measurement was to reconstruct the shower distribution and to extract the energy resolution of the whole array.

First of all, a calibration relative to the central crystal had to be performed during the analysis of the test measurement. The relative calibration is needed to ensure that a certain channel number in one crystal corresponds to the same channel number in all other crystals. Because of this calibration, the reconstruction of the shower and the calculation of the energy resolution became possible. The following result was obtained for the energy resolution:

$$\frac{\sigma}{E} = \frac{-0.132\%}{\sqrt{E}} + \frac{2.632\%}{E} - 0.283\%$$

With this, the value at 1 GeV could be extrapolated:

$$\frac{\sigma}{E}@1GeV = 2.22\%$$

The results are well, if one takes the problems into account which occurred during the beam time at MAMI. LAAPDs seem to be an optimal solution.
for the readout of the scintillator elements.

In the future, there are going to be experiments with larger crystal arrays. Soon, there will be a test measurement with an array consisting of 60 PWO-II crystals with LAAPD readout.
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References

[1] The PANDA Experiment at FAIR
   Ralf Kaiser for the PANDA Collaboration
   Povh, Rith, Scholz, Zetsche; Springer-Verlag, 2004
[4] Inorganic Scintillators - a basic material for instrumentation in physics
   Rainer Novotny, 2004
[5] Test and Developments of Crystals for a High-Resolution Electromagnetic Calorimeter for PANDA
   Master Thesis by Sophie Ohlsson, 2004
[7] Fast and Compact Lead Tungstate-Based Electromagnetic Calorimeter for the PANDA Detector at GSI
   Rainer Novotny, 2004
[8] The Electromagnetic Calorimeter of the future PANDA Detector
   Rainer Novotny for the PANDA Collaboration, 2006
[9] Characteristics and use of Si APD
   Hamamatsu Photonics, 2004
[12] Calorimeter readout with large area avalanche photodiodes
   Michaela Thiel, talk, 2005
[13] Detection of Monochromatic Photons between 50 and 790 MeV with a PbWO4-Scintillator Array
[14] Test measurement of 3x3 and 5x5 PbWO4 crystal matrix with the beam of γ-quanta
   Valera Dormenev, talk, 2007
[15] Energy response of 3x3 Emc matrix to photons
   Thierry Mertens, talk, 2007