4. The PANDA Electromagnetic Calorimeter

One of the important components of the PANDA spectrometer is the Electromagnetic Calorimeter (EMC). The PANDA detector consists of target and forward EMC. The target EMC surrounds the interaction point and provides an almost 4π coverage. It consists of three parts - Barrel, Forward and Backward Endcaps. The EMC of the forward spectrometer will employ a Shashlyk type calorimeter. Figure 4.1 displays the main parts of the EMC in the target spectrometer on the left side and the forward-spectrometer EMC on the right side.

The EMC was designed to achieve an almost 4π coverage for the detection of photons, electrons, and positrons in the target spectrometer. The forward spectrometer is located 7 m downstream of the target and will cover an area of about 3 m².

Due to the expected high annihilation rate of $2 \cdot 10^7$ annihilations/s, a calorimeter with a fast signal response is required. Further, the calorimeter needs to cover a wide dynamic range for energy deposition in individual crystals from 10 MeV up to 10 GeV. This range is dictated by the physics program of the PANDA experiment, which aims at precision spectroscopy of charmonium states and of exotic hadrons in the charmonium region. These demanding requirements impose the deployment of fast and high-density crystals such as lead-tungstate (PbWO₄ or briefly PWO) inorganic scintillator crystals as detector material in the target EMC [7]. The scintillation light from these crystals will be measured by Large-Area Avalanche Photo Diodes (LAAPDs) and Vacuum Photo Triodes (VPT) as photo sensors and specially designed front-end electronics. In comparison to the LAAPDs the VPTs have lower gain and lower quantum efficiency. However, the VPTs are more radiation hard, have lower dark current and lower capacitance, which provides advantages for operation in a high hit-rate environment. Therefore, VPTs will be used in the regions where high hit rates are expected, i.e. in the most-forward region of the target EMC.

The target electromagnetic calorimeter of PANDA will consist of about 17000 PWO
crystals. The optimization of the front-end electronics is the focus of this thesis and will be described in the following chapters.

This chapter will review the physics of photon interactions with matter, the properties of the detector material and the characteristics of the LAAPD photo sensors which were used for all the measurements described and evaluated in this thesis. The readout chain will employ the same preamplifiers for the VPTs and the LAAPDs, which results in the same waveform for both types of photo sensors. Therefore, the obtained results with LAAPDs can be applied as well to evaluate the performance of the VPTs.

4.1 Photon interactions with matter

When a high-energy photon interacts with matter it likely produces a pair of an electron and a positron with still high energies. The generated electron and positron interact with matter and can cause bremsstrahlung [35] of considerable energy. The bremsstrahlung photon again gives rise to electron-positron pair production. Thus, a cascade of many electromagnetic particles with gradually lower energy will build up until the energy of the particles falls below the threshold for pair production. The remaining energy is dissipated by excitation and ionization. Figure 4.2 shows the cross section of different processes of photons and electrons as a function of their energy. The main physics of photon interaction with matter is described briefly below:

**Bremsstrahlung**: The principal source of energy loss of high-energy electrons or positrons passing through matter is bremsstrahlung resulting from Coulomb interactions with the electric field of atomic nuclei. The energy spectrum of the radiated photons behaves like \(1/E\) – where \(E\) is the energy of the bremsstrahlung photon. In the limit of very hard bremsstrahlung the entire kinetic energy of an electron can be emitted as a photon but this is a very rare case. In general, the bremsstrahlung photons carry only a small fraction of the kinetic energy of the charged particle. The direction of the initial particle changes slightly during such a process. The energy loss of an electron by bremsstrahlung is approximately proportional to the electron kinetic energy. The interaction of photons with matter can be explained by three basic processes – the photoelectric effect, Compton scattering, and pair production [35, 36].

**Photoelectric effect**: At low energies, an atom absorbs a photon and emits an inner-shell electron. The atom is put into an excited state by this process and will return into its ground state by emission of Auger electrons or X-rays. The cross section for the photoelectric effect depends strongly on the electron density and thus on the \(Z\) of the absorber material.

**Compton scattering**: When a photon undergoes Compton scattering it transfers part of its energy and momentum to an atomic electron that is freed into an unbound state. The process will result in a free electron and a scattered photon. For most absorber materials, Compton scattering is by far the most likely process for photons with energies between a few hundred keV and a few MeV.

**Pair production**: Photons with energy of at least twice the electron rest mass (1.02 MeV) can produce an electron-positron pair in the Coulomb field of an atomic nucleus or an electron. The cross section for this process rises with energy and reaches an asymptotic value at very high energies (> 1 GeV). For energies above a few MeV (depending on the absorber material), pair production becomes the dominant photon interaction process.

**Radiation length**: The appropriate length scale to describe the development of an electromagnetic shower is the radiation length \(X_0\). One radiation length is the mean distance over which the electron energy is reduced to 1/e of its original value due to radiation loss.
only. The mean free path of a high energy photon for pair production is $9/7$ of a radiation length [35]. The radiation length is, therefore, a characteristic distance for the two processes that shape the electromagnetic cascade. The radiation length in a material is usually measured in g/cm$^2$. It can be approximated by [35]:

$$X_0 = \frac{A \cdot 716.4 \ g \cdot cm^{-2}}{Z \cdot (Z + 1) \cdot \ln(287/\sqrt{Z})} \quad (4.1)$$

where $A$ is the atomic mass and $Z$ is the atomic number of the material. To measure the energy of an incoming particle the calorimeter must be thick enough in terms of radiation lengths to fully contain the electromagnetic shower. To achieve this for the PANDA EMC, the high-$Z$, high-density lead-tungstate material was chosen with a crystal depth (i.e. length) of at least 22 radiation lengths [7].

The following equation describes the amount of energy loss by bremsstrahlung:

$$- \frac{dE}{dx} = \frac{E}{X_0} \quad (4.2)$$

where $dE/dx$ is the specific energy loss, $E$ is the energy of the particle, and $X_0$ is the radiation length given in (4.1). On the contrary, charged particles in the electromagnetic shower loose energy continuously by ionizing the traversed material.

### 4.2 Electromagnetic Shower

If the incoming photons have high energy, it is most likely that pair production occurs. In this process, the photon converts into an electron-positron pair. The electron and the positron undergo bremsstrahlung and are therefore deflected. Subsequently, a photon is emitted which again can produce an electron-positron pair if the energy is high enough. The shower process may spread in all directions, but is mainly focused in the longitudinal direction because of the high incoming longitudinal momentum. Figure 4.3 illustrates the development of such a cascade as a function of the radiation length. The shower continues
until the critical energy $E_c$ is reached. $E_c$ is the electron energy at which the cross section of bremsstrahlung becomes equal to that of pure ionization [36]. Therefore, the shower development 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:

$$E_c = \frac{550 \text{MeV}}{Z} \quad (4.3)$$

It is obvious that a material with a high $Z$ value corresponds to a low critical energy and is thus more sensitive to the full energy deposition.

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:

$$R_M = 0.0265 \times X_0(Z + 1.2) \quad (4.4)$$

The Moliere radius $R_M$ is a good scaling variable for describing the transverse dimension of an electromagnetic shower.

**Fluctuations:** The number of electrons and positrons in a shower produced by a photon with a given energy fluctuates statistically. Since the total ionization signal is proportional to the number of charged particles, the reconstructed energy fluctuates in the same way. The relative width of the distribution is equal to $\frac{\sqrt{n}}{n} = \frac{1}{\sqrt{n}}$ where $n$ is the number of charged particles. Therefore, the relative precision of the energy measurement with a calorimeter can be expressed as

![Figure 4.3: Illustration of an electromagnetic shower [38].](image)
\[
\frac{\sigma_E}{E} = \frac{b}{\sqrt{E}} \quad (4.5)
\]

One can see from this formula that the relative energy resolution of a calorimeter improves with the energy. Therefore, calorimeters are very attractive instruments for high-energy particle physics experiments.

The energy resolution of a calorimeter can be expressed in terms of the parameter \( b \), which is a stochastic term related to intrinsic shower fluctuations and photo-electron (phe) statistics. In practice, equation 4.5 has to be extended by adding a noise term \( c \) and a constant term \( a \) to account for instrumental effects independent of the shower development like non-uniform absorber thickness. This leads to [37]:

\[
\frac{\sigma_E}{E} = a + \frac{b}{\sqrt{E}} + \frac{c}{E} \quad (4.6)
\]

At moderately high energies, the noise term \( c \) becomes small and can be safely neglected. For very high energies, the stochastic (sampling) term becomes small and the resolution of the calorimeter is determined by instrumental effects represented by the parameter \( a \).

### 4.3 PbWO\(_4\) crystals as detector material

To detect high-energy photons, the EMC detector material should have the following properties. A high density and a short radiation length are required to allow for small size crystals and a compact EMC; a high light yield is needed to obtain the best energy resolution. Therefore, to detect high-energy photons, electrons and positrons with high energy-, time- and position-resolutions, the PANDA EMC will employ lead-tungstate crystals PbWO\(_4\) (PWO) [39]. PWO material is being used in the electromagnetic calorimeters of the CMS (ECAL) [32] and ALICE (PHOS) [33] experiments at CERN. However, in the meantime, through continued development efforts the PWO material has been improved to achieve the PWO–II material for the PANDA EMC. PWO-II has two times higher light yield [7] compared with PWO applied in the CMS experiment.

One of the key features of PWO is the fast scintillation process with a short decay time. Due to the short decay time, the PWO material is advantageous at high event rates as they are expected in PANDA at high antiproton annihilation rates. The short decay time is useful to get precise timing information as well. The PWO material has a short radiation length of about 0.89 cm [7] and the Moliere radius is 2.2 cm [7].

The main properties of PWO-II crystals are presented in table 4.1. The light luminescence yield compared to NaI(Tl) is very low, only about 1%. However, cooling PWO down to -25 °C improves the light yield by a factor 4 [7]. Full-size 200 mm long crystals deliver a light yield of 17-20 phe/MeV at 18 °C measured with photomultiplier [7] with bi-alkali photocathode (quantum efficiency ~20%). Figure 4.4 shows a photograph of lead-tungstate crystals used in the test measurements.
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Figure 4.4: Two samples of PWO-II crystals with dimensions ca. 20×20×200 mm$^3$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PbWO$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8.28 g/cm$^3$</td>
</tr>
<tr>
<td>Radiation length</td>
<td>0.89 cm</td>
</tr>
<tr>
<td>Moliere radius</td>
<td>2 cm</td>
</tr>
<tr>
<td>Luminescence peak wavelength</td>
<td>420 nm</td>
</tr>
<tr>
<td>Decay time</td>
<td>5 - 15 ns</td>
</tr>
<tr>
<td>Relative light output (NaI(Tl))</td>
<td>0.6% at RT 2.5% at -25 °C</td>
</tr>
</tbody>
</table>

Table 4.1: Main properties of PbWO$_4$ (PWO-II) [7].

4.4 Large-Area Avalanche Photo Diode

The operation of the electromagnetic calorimeter in the magnetic field of the target-spectrometer solenoid excludes the use of photomultiplier tubes for the readout of the PWO crystals. For that reason, a photo sensor is required which is insensitive to magnetic fields. Due to the low light yield of lead-tungstate the photo sensor should have internal gain. Large Area silicon Avalanche Photo Diodes (LAAPDs) satisfy these requirements and are therefore an ideal solution for the PANDA calorimeter.

Photo diode operation: When a photon enters a photo diode, 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 and silicon becomes sensitive to wavelengths shorter than 1100 nm. Two terms, needed to describe this sensitivity, are called the photosensitivity $S$ and the quantum efficiency $QE$. $S$ is given by the photo current divided by the incident radiant power and $QE$ is the ratio of generated electron-hole pairs over the number...
of incident photons (%). The following equation connects these two terms:

\[ QE = \frac{S \cdot 1240}{\lambda} \times 100\% \] (4.7)

where \( \lambda \) is the wavelength of the incoming photon. Figure 4.5 shows a schematic view of a silicon APD with reverse-bias structure. The photons enter the APD via the p\textsuperscript{++} layer. They are absorbed in the p\textsuperscript{+} layer where the electron-hole pairs are generated. Due to the electric field, the electrons drift towards the n\textsuperscript{++} side and the holes towards the p\textsuperscript{+} side. If the electric field is sufficiently high, these charge carriers will likely collide with the crystal lattice where 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. The charge collection of all the produced electrons takes place in the n\textsuperscript{++} region. A passivated layer made of silicon nitride (Si\textsubscript{3}N\textsubscript{4}) is mounted in front of the p\textsuperscript{++} layer to reduce the decrease of quantum efficiency caused by reflection losses.

![Figure 4.5: Schematic view of an APD with reverse-bias structure [7].](image)

The internal current gain of an APD becomes higher, when the applied reverse voltage increases. There are various expressions for the multiplication factor \( M \) of an APD. An informative equation is given below [40]:

\[ M = \frac{1}{L} \left( 1 - \int_0^L \alpha(x) dx \right) \] (4.8)

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

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 [40]:

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where $k$ 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.

**Large-Area Avalanche Photo Diode developments:** APDs for the readout of PWO crystals have already been developed for the CMS experiment at CERN [32]. These APDs have several advantages: compactness with an overall thickness of about 200 μm, low cost, insensitivity to magnetic fields and a high quantum efficiency of approximately 70%. A disadvantage of these APDs is their relatively small active area of $5 \times 5$ mm$^2$ compared to the area of the crystal end faces. For that reason, the development of large-area avalanche photo-diodes by Hamamatsu [41] with an active area of $10 \times 10$ mm$^2$ was initiated by the PANDA collaboration. The LAAPDs for PANDA will have the same internal structure as the APDs for CMS (see Figure 4.5). In the final PANDA setup there will be two rectangular LAAPDs attached to one end-face of the PWO crystal. Figure 4.6 shows a picture of standard APDs and LAAPDs to compare the different sizes of the active areas.

The crystals used for the test measurement at the MAMI accelerator, Mainz, Germany, have an end face area of $4$ cm$^2$ and were covered with one square LAAPD of $1$ cm$^2$. Cooled down to -25 °C PWO–II crystals yield about 500 photons per MeV. The applied square LAAPDs have a quantum efficiency of 75%. Therefore, the resulting signal of the LAAPD is generated by 94 electron-hole pairs per MeV [7].

![Figure 4.6](image)

**Figure 4.6:** Photograph of two standard ($5 \times 5$ mm$^2$) APDs, one square LAAPD ($10 \times 10$ cm$^2$), and one rectangular ($7 \times 14$ mm$^2$) LAAPD [41].