8. Evaluation of PANDA EMC performance

The rich PANDA physics program aims particularly at precise hadron spectroscopy. Whether the goals of the program can be reached depends crucially on the performance of the PANDA EMC. The Technical Design Report (TDR) [7] defined the requirements for the EMC readout electronics. The performance studies of the readout electronics, outlined in previous chapters, provided satisfactory results indicating that the requirements suggested in the TDR can be fulfilled.

In this chapter the performance results obtained from the Proto60 experiment will be used as input to basic simulations in order to assess the merits for physics results obtained with the PANDA EMC. Simulations are performed with PandaRoot [80], the general simulation and reconstruction software package developed for the PANDA experiment. Results will be discussed for single photons hitting a 3×3 crystal array and for the decay of the h_c charmonium into 7 γ detected with the PANDA EMC. For the 3×3 crystal array the energy resolution for single photons has been obtained and the influence of noise level and threshold on resolution and efficiency has been studied. In the study of the h_c charmonium state the simulation is performed for the entire EMC to demonstrate how the noise level and the cluster threshold affect the width of the reconstructed invariant mass.

8.1 Single photon simulations

In order to validate the Monte Carlo simulation setup, simulations were done with single photons of 200 MeV energy hitting the central crystal of a 3×3 crystal array. The crystal shape is the same as used in the Proto60 setup. The rms width of the noise level for this simulation was 0.3 MeV and the threshold for individual crystals was set to 1 MeV, exactly as was done for the Proto60 experimental setup (Chapter 6). Figure 8.1 shows the experimental data and the simulated data for the electromagnetic shower shape detected in a 3×3 PWO crystal array. The simulations agree with the experimental result except for small deviations in the corners of the crystal matrix. Such deviations are caused by the non-uniformity of the light collection inside the PWO crystal due to the tapered geometry of the crystals [81].

The deposited energy is summed up for all the crystals. In Figure 8.2 the line shape of the energy deposition spectrum fitted by an asymmetric Gauss function is shown. The obtained simulated resolution \((FWHM/2.355)/E\) is 4.24%. The corresponding experimental resolution, parametrized in Figure 6.34 with the parameters \(a=0.35\%\) and \(b=1.97\%\), is 4.76% and agrees with the simulated value within 11%.

Subsequently, for the same 0.3 MeV noise level and 1 MeV threshold, simulations were performed with photon energies up to 1.2 GeV energy. In Figure 8.3 top, the relative energy resolution determined as \((FWHM/2.355)/E\) (%) is shown as a function of the photon energy \(E\). In the bottom figure, the simulations and data from the PANDA EMC Technical Design Report [7] are shown for comparison. We observe good agreement of both simulations in the
low energy region, but a 23% difference at 1 GeV photon energy. The simulations in the TDR were done within a different framework using a different energy transport model than presently implemented in PandaRoot [82].

**Figure 8.1:** The electromagnetic shower shape for 200 MeV photons hitting the center of a 3×3 PWO crystal array: the black dashed lines and the red solid lines represent the experimental data and the simulations, respectively.

**Figure 8.2:** Simulated line shape of the energy deposition spectrum at the photon energy $E_\gamma = 0.2$ GeV.
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Figure 8.3: The simulated and experimental energy resolution \((\text{FWHM}/2.355)/E\). Top: the simulation performed for the \(3\times3\) crystal matrix. Bottom: The simulation with experimental data from the PANDA EMC TDR [7].

The energy resolution obtained in simulations for the interaction of 200 MeV photons with the \(3\times3\) crystal array agrees within about 10% with the experimental result for Proto60. Subsequently, the energy resolution of photon clusters is simulated for different noise levels and thresholds. In Figure 8.4 the dependence of the cluster energy resolution on the noise level of individual detectors is shown. The threshold was set to 1 MeV. We notice that the resolution worsens rapidly with increasing noise level of the readout electronics, i.e. by 25% for an increase of the noise level by a factor 5.

In order to avoid significant noise contributions to the summed cluster energy, the threshold for each individual detector should be set above the noise level, preferentially to a level equivalent to 3 times the RMS width of the noise level. The effect of the individual detector threshold on the energy resolution was investigated for simulations of 200 MeV photons hitting the \(3\times3\) crystal array. The RMS width of the noise level was fixed in this case to 0.3 MeV and the simulation was run for threshold values between 2 MeV and
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Figure 8.4: The cluster energy resolution for different noise levels of the readout electronics.

Figure 8.5: Top: The energy resolution for 200 MeV photons detected in a $3 \times 3$ crystal array for different photon thresholds. Bottom: Simulation from the PANDA EMC TDR [7] with complete shower collection. The energy resolution is shown for photon energies up to 1 GeV and different noise levels corresponding to different photon thresholds.
10 MeV. The resulting dependence of energy resolution on the threshold value is presented in Figure 8.5. The energy resolution for photon clusters gets worse for a higher threshold on the energy deposition in each crystal, caused by reducing the number of detected photons. Most of the energy is deposited in the central crystal and the deposited energy in the neighboring detectors quickly drops below the threshold. For comparison to the present simulations, the results from the PANDA EMC TDR [7] are shown in the bottom part of Figure 8.5. The same trend in the dependence of energy resolution on noise level and threshold is observed but, at 200 MeV photon energy, our simulation predicts a worse resolution. The simulation presented in Figure 8.5, bottom panel, was performed for the PANDA EMC with complete shower collection in a dynamically-defined cluster of neighboring crystals. Due to the more complete shower collection, the energy resolution is improved in this case. Therefore, we observe the slight discrepancy between our simulation result and the simulation performed for the TDR [7]. The observed dependence of the energy resolution on the noise level emphasizes the need to keep the detector noise level as low as possible.

8.2 Simulations of the $h_c$ charmonium state

Based on the performance characteristics of the newly-developed electronics we demonstrate by Monte Carlo studies the ability of the PANDA EMC to detect and analyze charmonium states with the example of the $h_c$ charmonium state. In addition, we show how the noise level, the threshold for individual detectors and the cluster threshold will influence the reconstructed mass and width of this state. For these studies the $h_c$ state was chosen since its all-neutral decay channel depends crucially on the ability of the EMC to detect multiple photons with high resolution:

$$h_c(1P_1) \rightarrow \eta_c + \gamma \rightarrow \eta + \pi^0 + \pi^0 + \gamma \rightarrow 7 \gamma.$$  

The invariant mass of this state will be reconstructed from the energy deposition of $7 \gamma$ in the EMC. The realistic simulation of this decay channel requires the response of the complete EMC.

The $h_c$ state is the $1P_1$ charmonium state (Chapter 2) and according to the recent PDG table its mass is $3525.42 \pm 0.29$ MeV [68]. Studies of the $h_c$ state, in particular its precise width, will help to understand the hyperfine structure (or spin dependence) of QCD bound states. The $h_c$ was observed first in the CLEO experiment in electron-positron annihilations: 

$$e^+e^- \rightarrow h_c \rightarrow \eta_c + \gamma$$  

The determined mass of the $h_c$ state was $3524.4 \pm 0.6 \pm 0.4$ MeV/$c^2$. The mass and width of the $h_c$ state was studied recently in the BES III experiment and the branching ratio for $h_c \rightarrow \eta_c + \gamma$ is $54.3 \pm 6.7 \pm 5.2\%$ [84]. The actual measured mass is $3525.40 \pm 0.13 \pm 0.18$ MeV/$c^2$ and the width $0.73 \pm 0.45 \pm 0.23$ MeV [84] is limited by the experimental accuracy. Due to the narrow width < 1 MeV of the $h_c$ state, a more precise experiment is required. For more detailed investigations, the anti-proton proton annihilation experiment PANDA will be able to measure the width of the state with much higher precision. The precision of the measurement with PANDA will be achieved by using the “resonance scanning” technique (see Chapter 2) exploiting the high-resolution HESR beam. The HESR will be run in two modes, the high-luminosity mode with a luminosity of $10^{32}$ $s^{-1}$ $cm^{-2}$ and the high-resolution mode with $10^{31}$ $s^{-1}$ $cm^{-2}$ [7]. For the high-luminosity mode of the HESR a production rate of the $h_c$ charmonium state of 82 events/day is expected. In the high-luminosity mode the annihilation rate will be 20 MHz and each crystal in the Barrel EMC and the Forward Endcap EMC will produce an average signal (or event) rate of 100 and 500 kHz, respectively. This high rate will cause pile-up signals in individual detectors. The probability of pile-up of one signal with k other signals is described by the
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Poisson distribution:
\[ P(k, \lambda) = \frac{(\lambda e^\lambda)^k}{k!} \]
with the rate parameter \( \lambda = \text{(event rate)} \times \text{(pulse width)} \). For pile-up of two signals we have \( k = 1 \). From the Proto60 signal analysis (Chapter 6) we derived that the optimized width of the differentiated signal is >200 ns; as a worst case we assume 300 ns. For 500 kHz event rate the probability of pile-up will be 12.9%. In Table 8.1 the pile-up probability is shown for different event rates for the Barrel and the Forward Endcap EMC.

<table>
<thead>
<tr>
<th>Annihilation rate (MHz)</th>
<th>Barrel EMC</th>
<th></th>
<th></th>
<th>Forward Endcap EMC</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Event rate (kHz)</td>
<td>100</td>
<td>150</td>
<td>Event rate (kHz)</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td></td>
<td>Pile-up Probability (%)</td>
<td>2.9</td>
<td>4.3</td>
<td>Pile-up Probability (%)</td>
<td>12.9</td>
<td>17.7</td>
</tr>
</tbody>
</table>

Table 8.1: Pile-up probability for Barrel and Forward Endcap EMC for different annihilation rates (resulting in the given event rates).

As mentioned before, the envisaged average annihilation rate will be in the order of 20 MHz. However, the target structure in the PANDA experiment will not be uniform due to fluctuations in size and frequency of the frozen hydrogen pellets. Thus, the event rate in a single Forward Endcap detector is estimated to increase [85] from 500 kHz to a peak rate of about 750 kHz. In order to avoid pile-up due to high event rates, the detector response has to be short enough. The designed readout electronics with the newly-developed feature-extraction algorithm will help to reduce the pile-up probability to the lowest possible values. In addition, the concept of the trigger-less data acquisition, proven in this thesis, will allow reaching higher event-selection efficiency and thus the largest possible amount of good data events. If the average luminosity needs to be limited because of fluctuating data rates, PANDA will still be able to collect a large amount of high-quality data.

In addition, the performance of the readout electronics is playing a crucial role for the measured width of the reconstructed invariant mass. In the previous section we saw, that the energy resolution is sensitive to the noise level of the electronics, the threshold for the individual crystal, and the cluster threshold. To see how the performance of the readout electronics affects the reconstruction of the invariant mass, the PandaRoot simulations were performed for different noise levels, single-crystal thresholds and cluster thresholds. In these simulations a cluster is defined as the group of crystals which measure an energy deposition above a certain energy threshold. In Figure 8.6 the invariant mass distribution of the \( h_c \) charmonium state reconstructed from 7 photons is shown.

The detection of low-energy photons from the electromagnetic shower is important to obtain the optimal energy resolution. However, the detection threshold has to be set high enough to suppress noise and wrongly-reconstructed photons from statistical fluctuations of the electromagnetic shower [7]. Simulations were performed with photon cluster thresholds
in the range 20 MeV - 50 MeV. The noise level for each channel of the readout electronics was kept fixed at the lowest possible level of 0.3 MeV and the threshold for individual detectors was 1 MeV (Chapter 5). In addition, for comparison a simulation was performed with a higher noise level of 1 MeV and a corresponding energy threshold of 3 MeV. In Figure 8.7 the reconstructed width (top) and the reconstruction efficiency (bottom) for the \( h_c \) state are shown for different cluster threshold values obtained at two different noise levels of the readout electronics and the corresponding thresholds for the single crystals. We observe that the width gets larger with increasing noise level in the readout electronics, and, moreover, the efficiency drops with an increasing threshold in the single crystals.

**Figure 8.6:** The invariant mass distribution reconstructed from 7 photons showing the \( h_c \) charmonium peak at \( 3531 \pm 1.28 \text{ MeV/c}^2 \).

**Figure 8.7:** The width (left) and reconstruction efficiency (right) of the \( h_c \) charmonium state for different cluster thresholds.

In addition, we observe that the reconstructed width increases and the reconstruction efficiency decreases with increasing cluster threshold. In order to see the influence of the noise level, simulations were performed for noise levels between 0.5 MeV and 3 MeV for a photon cluster threshold fixed at 20 MeV. The results are shown in Figure 8.8. We observe that the simulated width of the \( h_c \) charmonium state is significantly influenced by the noise level in the readout electronics. It is, therefore, mandatory to put every effort into reducing
the noise level as much as possible.

Figure 8.8: The simulated width of the $h_c$ charmonium state for different noise levels of the readout electronics for the PANDA EMC.

8.3 Conclusion

The PandaRoot simulations are validated by comparison to measurements with single photons hitting a $3 \times 3$ crystal array. The simulation and the experimental data show good agreement. The photon energy resolution is studied for different noise levels and single crystal thresholds. It has been shown, how the cluster energy resolution depends on the noise level and on the thresholds.

In order to demonstrate, how the performance of the EMC influences the reconstruction of charmonium states, the $7\gamma$ decay channel of the $h_c$ charmonium state was simulated.

The width of the $h_c$ charmonium state was compared for different noise levels, thresholds of single crystals, and cluster thresholds. It has been shown that a high noise level in the readout electronics causes a worsening of the width estimation of the $h_c$ charmonium state. Therefore, in our electronics development it was of key importance to keep the noise of readout electronics as low as possible.

To avoid a strong influence of the noise of the readout electronics on the measured signal, the single EMC detector threshold has to be adjusted accordingly. We have shown that the width of the $h_c$ charmonium state gets worse at high threshold values and the efficiency decreases due to a reduction of the number of detected photons.

Low-energy photons and charged particles as well as noise can cause a wrong measurement of shower-energy and, therefore, a worsening of the reconstructed width of charmonium states. Thus, the width of the $h_c$ charmonium state was investigated for different cluster thresholds. We observed that the width and the efficiency get worse for high cluster thresholds. Figure 8.7 shows that width and efficiency improve for a lower noise level at the same cluster threshold, which underlines the need for the discussed noise-reduction techniques.

The simulation study of the performance for the PANDA EMC has shown that the EMC has to have the best performance in terms of noise level and high-rate capability, in order to be able to study narrow resonances.