Performance of Prototypes for the Barrel Part of the $\overline{\mathrm{P}}$ANDA Electromagnetic Calorimeter

Christoph Rosenbaum[1], S. Diehl[1], V. Dormenev[1], P. Drexler[1], M. Kavatsyuk[2], T. Kuske, S. Nazarenko[1], R. Novotny[1], P. Rosier[3], A. Ryazantsev[4], P. Wieczorek[5], A. Wilms[5] and H.-G. Zaunick[1] for the $\overline{\mathrm{P}}$ANDA collaboration

[1]II. Physikalisches Institut, Universität Gießen, Germany
[2]KVI-CART, University of Groningen, The Netherlands
[3]IPN Orsay, France
[4]IHEP Protvino, Russia
[5]GSI, Darmstadt, Germany

E-mail: christoph.rosenbaum@physik.uni-giessen.de

Abstract. The performance of the most recent prototypes of the $\overline{\mathrm{P}}$ANDA barrel electromagnetic calorimeter (EMC) will be compared. The first large scale prototype PROTO60 was designed to test the performance of the improved tapered lead tungstate crystals (PWO-II). The PROTO60 which consists of 6×10 crystals was tested at various accelerator facilities over the complete envisaged energy range fulfilling the requirements of the TDR of the $\overline{\mathrm{P}}$ANDA EMC in terms of energy, position and time resolution. To realize the final barrel geometry and to test the final front end electronics, a second prototype PROTO120 has been constructed. It represents a larger section of a barrel slice, containing the most tapered crystals and the close to final components for the $\overline{\mathrm{P}}$ANDA EMC. The performance of both prototypes will be compared with a focus on the analysis procedure including the signal extraction, noise rejection, calibration and the energy resolution. In addition, the influence of the non-uniformity of the crystal on the energy resolution will be discussed.

1. Introduction

The state-of-the-art $\overline{\mathrm{P}}$ANDA detector at the future FAIR facility will be used to study proton - antiproton interactions. The EMC of the target spectrometer with its expected excellent performance and efficiency for electromagnetic probes over a wide energy range from 10 MeV up to 15 GeV, will be one of the central components to achieve the physics goals. The barrel part of the EMC will consist of more than 11,000 lead tungstate crystals operated at $-25°$C to achieve the required performance and efficiency stated in the TDR of the $\overline{\mathrm{P}}$ANDA EMC [1].

2. Prototypes of the $\overline{\mathrm{P}}$ANDA barrel EMC

2.1. Characterization of the prototypes

In order to judge the performance of the prototypes, the emphasis of the analysis is put on the obtained energy resolution and energy threshold. The energy resolution is a crucial parameter for the $\overline{\mathrm{P}}$ANDA Barrel EMC because it has a strong impact on the accuracy of the invariant mass determination, such as of J/Ψ states. In addition, the energy resolution influences the determination of the E/p ratio of electrons and positrons. The following parametrization of the energy resolution was required by the TDR of the $\overline{\mathrm{P}}$ANDA EMC:

$$\frac{\sigma}{E} = \frac{2\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1\% \tag{1}$$

The statistical term, which is dominated by the Poisson statistics of the light collection process, is crucial in particular for low energy photons due to the relatively low light yield of PWO compared to other scintillator materials. The constant term of 1% is the resolution limit at high energies affected by crystal inhomogeneities, calibration and shower leakage.
The energy threshold influences the reconstruction of low energetic photons which are a major contribution to many background channels and have to be detected completely. On the other hand, the energy threshold is limited by the electronic noise of a single channel and the distribution of the deposited energy at low energies. The TDR of the EMC [1] states an energy threshold of photons of 10 MeV which requires to a single crystal threshold of ≤ 3 MeV.

2.2. PROTO60

The PROTO60 is the first real-size prototype of the $\overline{\mathrm{P}}$ANDA Barrel EMC and the geometry is arranged to resemble a subsection of a barrel slice. It consists of 60 PWO-II crystals which are read-out with only a single 1 cm^2 quadratic large area avalanche photodiode (LAAPD) and a low-noise low-power preamplifier [2]. The prototype is operated at $-25°$C. The performance has been studied during several beam tests over the complete energy range obtaining a sufficient energy, position and time resolution. Details can be found in [3]. The parametrization of the relative energy resolution of the PROTO60 for the total energy range from 50 MeV up to 15 GeV with an individual module threshold of 1 MeV can be described by [4]

$$\frac{\sigma}{E} = \frac{0.25\%}{E/\mathrm{GeV}} \oplus \frac{1.86\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1.46\%, \tag{2}$$

where the first component estimates the electronic noise contribution, while the other two correspond to the statistical term and constant term.

2.3. PROTO120

The PROTO120 represents a larger section of a barrel slice, containing 120 of the most tapered crystals. It is operated at $-25°$C and contains the close to final components for the $\overline{\mathrm{P}}$ANDA Barrel EMC. The readout is performed with two rectangular large area APDs per crystal, which are read out separately via the specially developed APFEL-ASIC preamplifier [5], providing a large dynamic range of 10,000 (1 MeV up to 10 GeV), low power consumption (55 mW/ch), a high rate capability up to 350 kHz and optimized signal shaping.

3. Results of beam tests with PROTO120

3.1. Setup

In April 2015 a first beam test with the PROTO120 was performed at the MAMI facility in Mainz. The goal was to investigate the response of the prototype to photons in the low energy regime. At MAMI, the electron beam is converted via Bremsstrahlung into a continuous and collimated photon beam using the Glasgow Photon Tagging Spectrometer which provided tagged photons up to 830 MeV. 16 crystals of type II of the PROTO120 were read out with a commercial SIS3302 sampling ADC (SADC) , but only a 3×3 sub matrix was considered for the analysis. Relatively short calibration runs were performed by directing the photon beam into each crystal and one longer run hitting the center of the 3×3 matrix.

Journal of Physics: Conference Series **742** (2016) 012015 doi:10.1088/1742-6596/742/1/012015

3.2. Analysis

The SADCs are continuously taking samples of each preamplified LAAPD pulse. A trace is stored in case of a postive trigger signal, which requires a coincidence of a logical OR of the selected tagger channels and the responding PWO matrix. A typical sampled event is depicted in Fig. 1 where also the extraction of the energy information is indicated. The deposited energy in a crystal is proportional to the signal amplitude. In a basic approach, the signal amplitude is obtained by subtracting the baseline and the pulse minimum. In order to add the information of both LAAPDs a relative calibration is required using the amplitude ratio. Before summing the energy response of the whole matrix, they have to be relatively calibrated using the direct photon beam. The tagged lineshapes of the calibrated and summed 3×3 matrix with a summation threshold of 2.7 MeV are depicted in Fig. 2. In order to obtain the energy resolution, the reconstructed lineshapes are fitted with a so-called Novosibirsk function [6], a commonly used function to describe the skewed Gaussian distribution. The Novosibirsk function is defined by

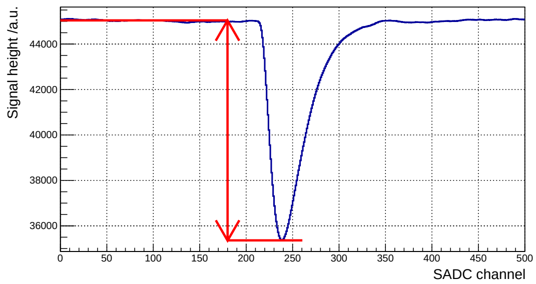

Figure 1: One sampled event (20 ns per bin) after shaping of the APFEL ASIC with indicated energy extraction.

$$f(x) = Ae^{-\frac{1}{2}\left(\frac{\ln^2(1+\Lambda\tau(x-\mu_{max}))}{\tau^2}+\tau^2\right)} \tag{3}$$

where $\Lambda = \frac{\sinh(\tau\sqrt{\ln 4})}{\sqrt{\ln 4}\tilde{\sigma}}$ is parametrized by the asymmetry τ, width $\tilde{\sigma} \equiv \frac{\mathrm{FWHM}}{2\sqrt{\ln 4}}$ and mode μ_{max} which is the value that is most likely to be observed in a measurement. The following parametrization of the energy resolution for the beam hitting the center of the 3×3 matrix could be obtained as

$$\frac{\sigma}{E} = \frac{0.16\%}{E/\mathrm{GeV}} \oplus \frac{2.46\%}{\sqrt{E/\mathrm{GeV}}} \oplus 2.32\%. \tag{4}$$

The electronic noise level can be studied in more detail by obtaining the distribution of the RMS of the baseline without presence of a signal. The mean value of this distribution leads

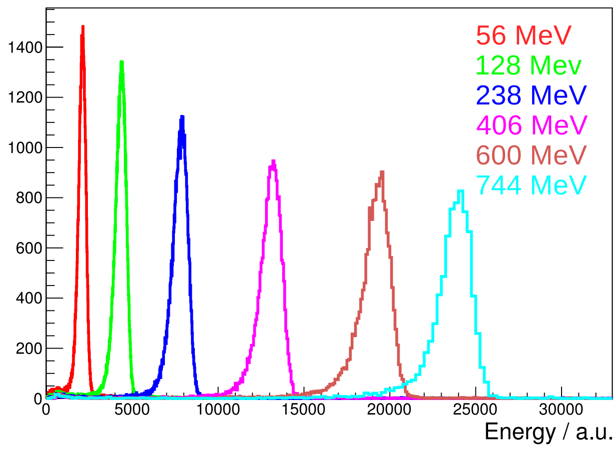

Figure 2: Tagged lineshapes of the calibrated and summed 3×3 matrix with a summation threshold of 2.7 MeV.

to an electronic noise level of 0.72 MeV. Basically, the electronic noise is the intrinsic noise of the preamplifier which comes from the input capacity of the preamplifier, in case of the PROTO120. The electronic noise can be translated directly to the summation threshold of a single crystal. The summation threshold corresponds to the level where most of the noise contribution is rejected. The noise distribution is expected to be Gaussian. Therefore, more than 99.7% of the events are within a $3 \cdot \sigma$-range. This range is usually set as the summation threshold. Hence, for the beamtime test a summation threshold was set to 2.7 MeV.

4. Influence of light collection non-uniformity on the energy resolution

To realize the barrel EMC geometry, crystals with different degree of tapering are used. The distribution of the light yield of differently tapered crystals, depicted in Fig. 3, is determined within the quality control with low energy gamma sources. Therefore, the crystals of the barrel EMC show a non-uniformity in light collection, which is a result from an interplay between the focusing and the absorption of light within the crystal. Since the focusing effect strongly depends on the degree of tapering, the resulting NUF curve varies with the type of crystal. While crystals with an average degree of tapering show a difference in light yield of $\sim$ 20% when created in the front or the rear part of the crystal, this value increases for the most tapered crystals up to 40% with a slope in the front part of almost 3 %/cm [7]. Furthermore, the non-uniformity in light collection causes a smearing of the energy response, resulting in a significant increase of the constant term of the parameterization of the energy resolution. This effect is dominant for energies above a few hundred MeV and can be reduced by de-polishing one side face of the crystals as it has been investigated by the CMS-ECAL collaboration [8]. However, since the reconstruction of low energy photons down to 10 MeV is essential for $\overline{\text{P}}$ANDA and due to the low light yield of PWO, de-polished crystals have not been considered so far. Nevertheless, an investigation has been started to study a 3×3 matrix with reduced non-uniformity. The analysis was performed in a similar manner. The obtained relative energy resolution for the 3 × 3 linearized crystal array can be parametrized by [9]

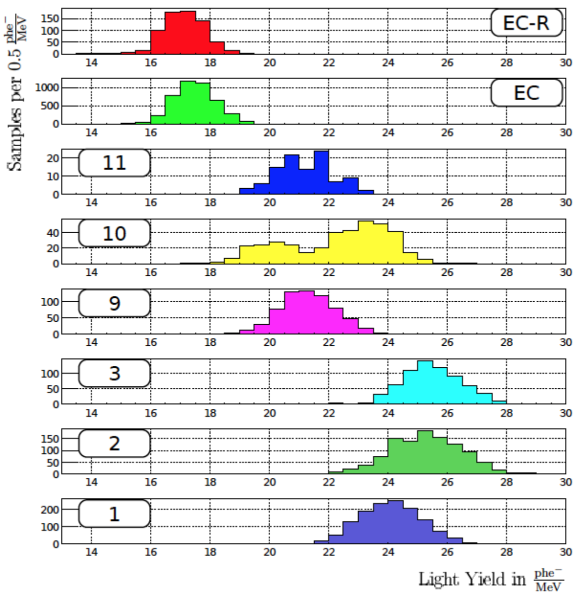

Figure 3: The larger the level of tapering, the higher the light yield output. The crystals of both end caps are almost rectangular (EC-R, EC). The type 1 has the most tapered geometry [1].

$$\frac{\sigma}{E} = \frac{0.27\%}{E/\text{GeV}} \oplus \frac{2.30\%}{\sqrt{E/\text{GeV}}} \oplus 0.50\%. \tag{5}$$

A comparison of both energies resolutions, depicted in Fig. 4, shows a significant improvement for higher energies and similar results for lower energies.

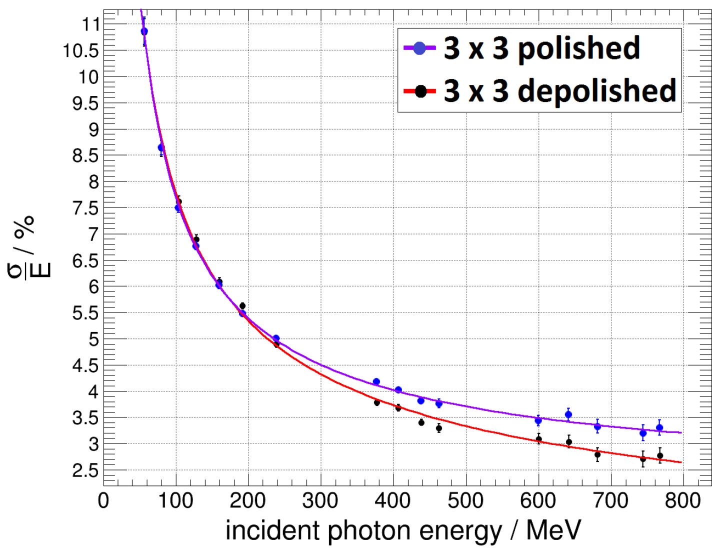

Figure 4: Energy resolution of the 3 × 3 matrix with polished and de-polished crystals, respectively, for photons impinging on the central crystal [9].

5. Conclusion

The response of both $\overline{\text{P}}$ANDA EMC prototypes fulfills the requirements of the TDR [1]. The study of the influence of the non-uniformity of the light collection on the energy resolution has shown that the performance of the $\overline{\text{P}}$ANDA barrel EMC could gain from a reduction of the non-uniformity. However, the de-polishing of the crystals should be done preferentially in the forward region of the barrel where higher photon energies are expected. Nevertheless, the effective noise of the PROTO120 is higher than of the PROTO60 and requires a further reduction of the noise level in particular due to pick-up and cross-talk.

6. Acknowledgments

This work was supported by BMBF, GSI and HIC4FAIR. The authors like to thank the staff of the MAMI facility for providing the beam.

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