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Impact of Non-Uniformity in Light Collection on the Energy Resolution of the PANDA Electromagnetic Calorimeter at Photon Energies Below 1 GeV

Stefan Diehl, Kai-Thomas Brinkmann, Peter Drexler, Valery Dormenev, Rainer W. Novotny, Christoph Rosenbaum and Hans-Georg Zaunick for the PANDA-Collaboration

2nd Physics Institute, Justus-Liebig-University Giessen, Heinrich-Buff-Ring 16, 35392 Giessen, Germany

E-mail: `stefan.diehl@exp2.physik.uni-giessen.de`

Abstract. The electromagnetic calorimeter (EMC) of the PANDA detector at the future FAIR facility comprises more than 15,000 lead tungstate (PWO) crystals. The barrel part will consist of 11 crystal geometries with different degree of tapering, which causes a non-uniformity in light collection as an interplay between the focusing and the internal absorption of the light. For the most tapered crystals the detected light is enhanced by 40%, if the scintillation process is created in the front part of the crystal. Due to the shower development and its fluctuations the non-uniformity leads to a reduction of the energy resolution. To reduce this effect, one lateral crystal side face has been de-polished to a roughness of 0.3 μm. Measurements confirm an increase of the light yield in the rear part of the crystal. In contrast, only a slight decrease can be observed in the front part. The overall non-uniformity is significantly reduced below 5%. This paper will discuss the experimental studies based on GEANT4 and optical simulations to understand the impact of a de-polished side face on the light collection. For consequences on the future performance, a 3x3 sub-array of de-polished crystals was directly studied using a tagged photon beam in the energy range from 50 MeV up to 800 MeV, respectively, performed at the tagged photon facility at MAMI, Mainz. The comparison to an array composed of polished crystals confirms a significant improvement of the constant term of the energy resolution from above 2 % down to 0.5 % and only a small increase of the statistical term. The results can be reproduced in GEANT4 simulations.

1. Introduction

The PANDA detector will be one of the central experiments of the future Facility for Antiproton and Ion Research (FAIR) which is currently under construction near Darmstadt in Germany. PANDA will be a fixed target experiment using a cooled antiproton beam of up to 15 GeV to study new aspects in the fields of hadron spectroscopy, nucleon structure investigations, the modification of hadrons in matter and the search and characterization of Hypernuclei [1]. The electromagnetic calorimeter (EMC) of the PANDA detector, which will be one of the central components to achieve the physical goals, will consist of more than 15,000 lead tungstate (PWO) crystals operated at -25 °C to increase the light yield [1]. To reach the physics goals, a detection of photons down to 10 MeV is mandatory.

2. Origin and reduction of the non-uniformity in light collection

The barrel part of the target EMC will be composed of 11 crystal geometries with a different degree of tapering. The read out will be performed with two rectangular large area avalanche photo diodes per crystal with an active area of 1 cm^2 each. Due to the tapering the crystals show a non-uniformity in light collection as a result of an interplay between the focusing and the internal absorption of the scintillation light within the crystal (see Fig. 1). The non-uniformity has been determined using low energy γ-rays, cosmic muons and a 80 MeV proton beam leading to comparable results (see also [2]). The measured non-uniformity curves for the two most tapered crystal types (1 and 2) and for a crystal with an average degree of tapering (type 6) are shown in Fig. 2.

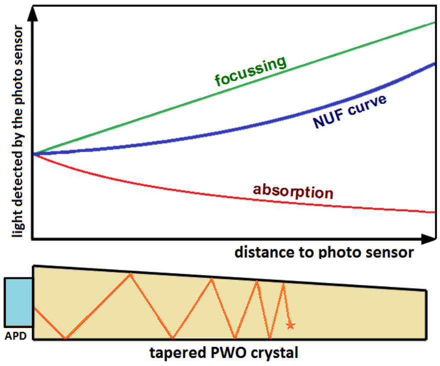

Figure 1. Illustration of the effects which contribute to the non-uniformity of the light collection.

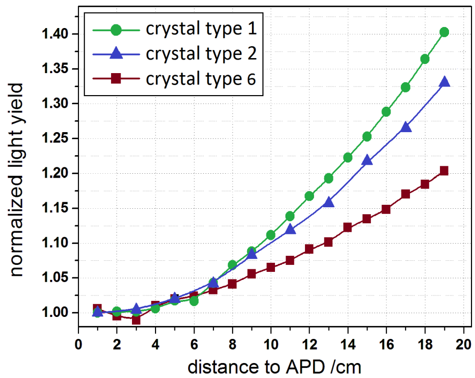

Figure 2. The measured non-uniformity curves of crystals with different degree of tapering.

While crystals with an average degree of tapering (type 6) show a light yield difference between creation of the scintillation light in the front and the rear part of the crystal of 20 %, this value increases for the most tapered crystals to more than 40 % with a slope in the front part of almost 3 %/cm. Due to the spread of the electromagnetic shower within the crystal and due to its fluctuations, this effect causes a smearing of the response leading to a reduction of the energy resolution, in particular the constant term. This problem has already been considered by the CMS-ECAL collaboration and was solved by de-polishing crystals on one lateral side [3]. Since the PANDA barrel EMC is focusing on much lower energies ranging from 10 MeV up to a few GeV, besides the uniformity of the light collection, also the absolute light yield has to be considered, if the crystal surface is modified. To investigate the impact of a de-polished side face on these parameters, the experiences from CMS [3] have been used and one lateral side face of a set of 25 crystals has been de-polished at the CMS setup to a roughness of $R_a = 0.3\ \mu$m.

Figs. 3 and 4 show the absolute and relative position dependent light yield of six typical type 2 crystals wrapped with mirror reflective VM2000 before and after the de-polishing procedure. As an effect of the de-polishing, a significant increase of the absolute light yield in the rear part of the crystal can be observed combined with a slight decrease in the front part. As a direct result, the non-uniformity is reduced down to a typical value of 5 % with a nearly homogeneous response in the front and central part of the crystal. The observed behaviour can be reproduced with the ray tracing model of GEANT4 (see Fig. 5). The increase of the light yield in the rear part of the crystal can be explained by photons which change their direction on the way to the front face of the crystal, which is illustrated by the significant increase of photons with path lengths between 1 cm and 39 cm in a crystal with a de-polished side face in Fig. 6.

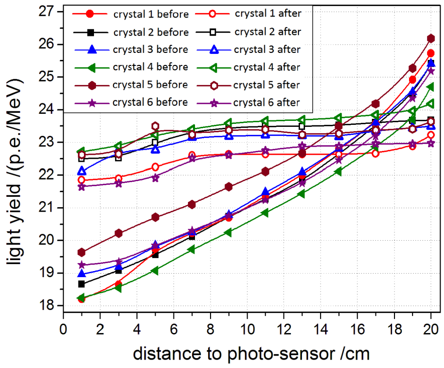

Figure 3. Absolute light yield of six typical type 2 crystals before and after de-polishing of one lateral side face.

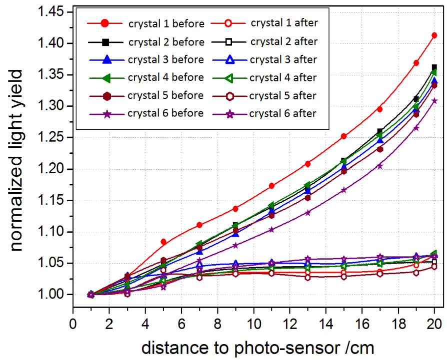

Figure 4. Relative light yield of six typical type 2 crystals before and after de-polishing of one lateral side face.

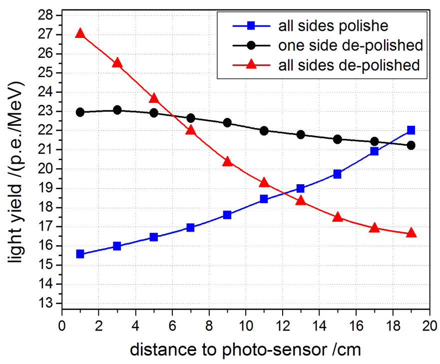

Figure 5. Simulated light yield of a completely polished crystal and a crystal with one / all lateral side faces de-polished. The crystal is wrapped with mirror reflective VM2000 in all cases.

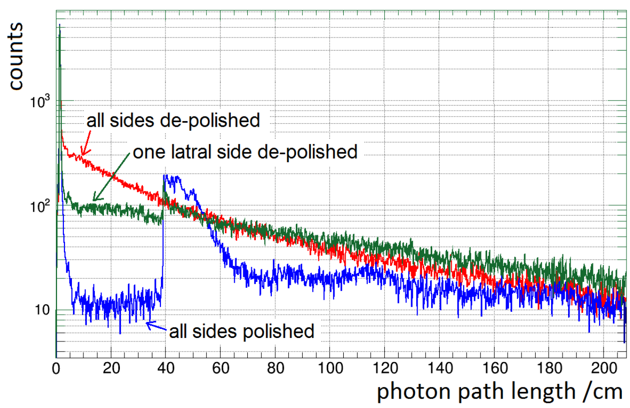

Figure 6. Path length distribution of photons which reach the photo-sensor emitted from a source positioned 1 cm away from the crystal rear face for different surface concepts.

3. Impact of the non-uniformity on the energy resolution of the PANDA barrel EMC

For the first time a 3x3 sub-matrix of de-polished crystals has been implemented in the current close to final barrel EMC prototype (see Fig. 7) and compared with an identical array of completely polished crystals. The response to tagged photons in the energy range between 50 MeV and 800 MeV, respectively, has been measured for a central interaction within the 3x3 array at the MAMI facility in Mainz (Germany). Fig. 8 shows the obtained energy resolution for the 3x3 sub-array of de-polished crystals in comparison to a similar matrix composed of polished crystals. The experimental results show a significant improvement of the energy resolution for energies down to 200 MeV if crystals with one de-polished side face are used, while the energy resolution is comparable for both arrays in the region between 50 MeV and 200 MeV, respectively. As a consequence, the constant term of the relative energy resolution is significantly reduced from above 2 % down to 0.5 % while the statistical term increases only slightly. The

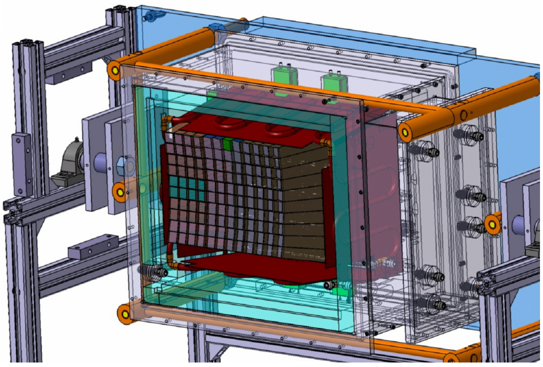

Figure 7. Schematic drawing of the current PANDA barrel EMC prototype PROTO120.

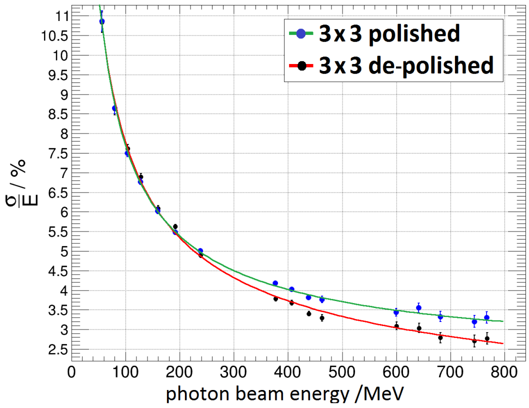

Figure 8. Relative energy resolutions of 3x3 arrays of de-polished and completely polished crystals operated at a temperature of -25°C implemented into PROTO120 [5].

shown results can be well reproduced with a specially developed GEANT4 model, including the non-uniformity and other empirical properties of the crystals and their readout. More details on the experimental and simulation procedure can be found in [4] and [5].

4. Conclusion and Outlook

The de-polishing of one lateral side face provides a nearly uniform response combined with an only moderate light loss in the front part of the crystal. On the other hand the light yield from the rear part of the crystal even increases due to a direction change of a certain amount of photons, initiated by the de-polished side face. Especially at high energies a significant improvement of the energy resolution can be achieved if the light collection is uniform. Due to the only moderate light loss in the front part of the crystal, no change of the energy resolution can be observed in the energy region between 50 MeV and 200 MeV, in the experimental data as well as in GEANT4 simulations.

5. Acknowledgements

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