High-quality PWO crystals for the PANDA-EMC

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Abstract. The paper provides a status report on the crystal production and quality control of a major part of the PbWO$_4$ crystals for the PANDA-EMC. The results confirm the excellent performance of the new generation of PWO-II. The mechanism of stimulated recovery provides an additional tool to recover radiation damage at room and low temperatures by applying an external infrared light source. Even on-line recovery can be considered if the photo sensor is insensitive in that particular wavelength region.

1. The target electromagnetic calorimeter of PANDA

The PANDA detector, one of the approved major experiments at the future FAIR facility at GSI (Darmstadt, Germany) is dedicated to the hadron-physics program exploiting the stored and cooled beam of anti-protons. The research program is focusing on charmonium spectroscopy, gluonic excitations, open and hidden charm in nuclei and gamma-ray spectroscopy of hypernuclei [1]. Figure 1 provides an overview of the target and forward section of the PANDA detector and marks the electromagnetic calorimeter EMC.

Figure 1. Schematic view of the PANDA detector including the EMC composed of a barrel and two endcap sections.

The electromagnetic calorimeter (EMC) of the target spectrometer is one of the major detector components to provide high-resolution photon and meson spectroscopy [2,3]. The calorimeter will

Figure 2. Schematic figure of the barrel and forward endcap as major components of the electromagnetic calorimeter of the PANDA target spectrometer.
have to cope with photons in the energy range starting already at a few tens of MeV up to several GeVs. A pair of large area avalanche photo diodes (LAAPD) or a vacuum photo triode (VPT) are foreseen as photo sensor of the individual crystal and both options allow operating in the magnetic field of the superconducting solenoid. Figure 2 illustrates two of the three major components of the calorimeter the barrel and forward endcap.

Irrespective of the finally collected percentage of the light yield, additional cooling of the scintillator reduces the thermal quenching of the scintillation processes and allows a significant improvement of the energy resolution, when photon statistics dominates. A temperature of $T = -25^\circ C$ was chosen as the operating temperature leading to a light increase of a factor of $\sim 4$ compared to room temperature.

1.1. The barrel of the target calorimeter
The layout of the barrel part comprises 16 identical slices. Each one consists of 710 tapered PWO crystals of 200mm length shaped in eleven geometries of two different symmetries. All crystals have a transversal size slightly above the Molière radius of 2.1cm. The 11,360 crystals are pointing slightly off the asymmetrically located target position.

Groups of four crystals are contained in a carbon fiber alveole including the two rectangular LAAPDs (active area $7 \times 14$mm²), the pre-amplification and shaping circuits. Low noise (<2MeV), power consumption and a dynamic range of 10,000 are achieved by a custom designed ASIC (APFEL). The concept of the electronics is based on typical count rates of >100kHz per module. All latter components will be integrated into the cold section ($T = -25^\circ C$) thermally shielded and temperature stabilized on the level <0.1°C. The mechanical support structure will house the complete electronics for control and digitization to minimize the required space for signal transfer out of the detector.

1.2. The endcaps
Both endcaps are designed in a similar manner. However, crystals are of identical and rectangular or slightly tapered shape pointing off the target. In order to cope with count rates well above 500kHz vacuum photo triodes (VPTs) are chosen at least for the most forward region.

2. The quality of PWO-II crystals produced at BTCP
Within the collaboration, the quality of PWO has been significantly improved primarily due to a reduced concentration of defects, achieved by raw material selection and growing technology. As a consequence, the co-doping with La- and Y-ions could be reduced to a level of <40 ppm. Therefore, full size crystals of 200mm length and nearly rectangular shape deliver on average 18 photoelectrons per MeV measured at room temperature (RT) using a phototube with bialkali photocathode. The careful selection of the raw material has strongly reduced those impurities, which lead to slow decay components in particular when the crystals are cooled.

After the approval of the Technical Design Report [3] the mass production at BTCP (Bogoroditsk Techno-Chemical Plant, Bogoroditsk, Tula Region, Russia) was started with very selective quality limits with respect to optical transmittance, homogeneity, light yield, scintillation kinetics and radiation hardness determined at room temperature.

The acceptance tests are performed in close collaboration with the CMS/ECAL collaboration at CERN exploiting the ACCOS [4] machine, which was adapted to the PANDA geometry and specifications. The measurements of radiation hardness and absolute light yield including crosschecks at low temperature as well as the final analysis are done at Giessen. So far, 7,355 crystals have been delivered and completely tested with an overall rejection rate of 7%.

2.1. The optical performance
The optical transmissions are measured longitudinally as well as perpendicularly to the crystal axis in order to control the homogeneity. Figure 3 shows the measured longitudinal transmission values at the relevant wavelengths of 360, 420 and 620nm, respectively. The figure confirms the consistency of the
measurements obtained at the three testing locations. All values are well above the specification limits \((T \geq 35\% \at 360\text{nm}; T \geq 60\% \at 420\text{nm} \text{ and } T \geq 70\% \at 620\text{nm})\) and none of the crystals had to be rejected due to insufficient optical quality. The maximum variation of the absorption edge along the crystal length, which is a sensitive measure of the optical homogeneity, is determined by the wavelength corresponding to a transmission value of \(T=50\%\) and remains well below \(\Delta\lambda<3\text{nm}\).

2.2. Light yield
The significantly improved light yield is documented in Figure 4. The detected number of photoelectrons per MeV deposited energy is determined at room temperature \((T=18\degree\text{C})\) with a standard photomultiplier with fused silica window and bialkali photocathode (Hamamatsu R2059, \(\text{QE}(420\text{nm})=21\%\)). The signal amplitude caused by \(\gamma\)-rays of a \(^{137}\text{Cs}\)-source (\(E_\gamma=662\text{keV}\)) is calibrated with the single-photoelectron peak.

**Figure 3.** The distributions of the longitudinal transmission at three selected wavelengths of 200mm long PWO-II crystals in PANDA geometry measured at three locations for comparison.

**Figure 4.** The distribution of the light yield measured at \(T=18\degree\text{C}\) with a photomultiplier tube for PWO-II crystals of 6 different PANDA geometries. The strongly tapered shapes (type 1, 2, 9 and 10) indicate the impact of light focusing.
Only a few samples do not pass the limit of 16phe/MeV. The further enhanced light yield of the barrel crystals reflects the light collection due to the more tapered crystal shape compared to the nearly straight geometry of the endcap module. The non-uniformity of light collection will be compensated by an appropriate reflector foil. More than 90% of the light is collected within 100ns, which even holds when crystals are cooled down to T=-25°C.

2.3. Radiation hardness

The most critical parameter is the change of the longitudinal absorption coefficient $\Delta k$ due to radiation damage. The crystals are irradiated at room temperature at the facility at Giessen with an integral dose of 30Gy using a set of $^{60}$Co sources (dose rate 4Gy/minute). The longitudinal transmission is measured up to a wavelength of 900nm delayed by 30 minutes after irradiation in order to exclude fast spontaneous recovery processes. The required value $\Delta k \leq 1.1m^{-1}$ at 420nm guarantees that light losses due to radiation damage within an experimental period of 6 months remain tolerable even if the detectors are operated at low temperature, which will be discussed in more detail in the next chapter. Figure 5 shows the distribution of the $\Delta k$ value at 420nm and indicates the significant percentage of extremely radiation hard crystals in the tail of the distribution towards lower values. All crystals above the limit of 1.1m$^{-1}$ are rejected. Radiation hardness appears to be the most selective quality parameter. The measurement at Giessen is compared to the data provided by the manufacturer.

![Figure 5](image)

Figure 5. Distribution of the radiation induced absorption coefficient $\Delta k$ measured at room temperature for PWO-II crystals. The integral dose amounts to 30Gy ($^{60}$Co). The specification limit amounts to $\Delta k \leq 1.1m^{-1}$ determined at the radiation facility at Giessen.

3. Recovery of radiation damage by stimulation with infrared light

3.1. Radiation damage of cooled PWO crystals

As investigated within the collaboration [4], [5], the recovery mechanisms become extremely slow at T=-25°C with time constants in the order of $\tau > 400h$. Dominated by the damaging process due to irradiation the light yield deteriorates asymptotically towards a final value. This is correlated with the radiation hardness expressed by $\Delta k$ being a measure of the concentration of defect centers in the crystal.

![Figure 6](image)

Figure 6. Correlation of the relative loss in light yield of cooled PWO-II detectors versus the induced absorption value at room temperature of investigated crystals. In both cases the integral dose amounts to 30Gy. The dotted line corresponds to a correlation coefficient of 0.95.
Such a correlation for a few accepted crystals is shown in Figure 6, which relates the relative loss of light yield of a cooled detector with the $\Delta k$ value at room temperature. The detector response is measured either with low energy $\gamma$-rays or the energy deposition of cosmic muons, respectively. Both values are determined applying an integral dose of 30Gy. Since only the most inner part of the forward endcap - corresponding to about 10% of the modules - has to cope with a dose rate of typically 20mGy/h for the maximum event rate of $2 \cdot 10^7$ pp- annihilations, a detector module will not lose more than 50% of the signal response if crystals with $\Delta k < 0.6 \text{m}^{-1}$ are selected. In that case the gain due to cooling still provides a net increase of at least a factor of two. In the barrel section, radiation damage will be 1-2 orders of magnitude lower.

### 3.2. Stimulated recovery of radiation damage at room temperature

It is well known that color centers, which are created during irradiation due to point structure defects or traps for electrons and holes, are leading to absorption bands in a wide spectral region but can be spontaneously relaxed after the end of irradiation via thermo-activation. Therefore, heating of the crystal is the standard procedure to anneal radiation damage, which requires the disassembly of the detector system. Even keeping the crystals in the dark, relaxation processes at room temperature are relatively fast and efficient to recover the crystals nearly completely during a typical beam-off period of $\sim 6$ months.

![Figure 7. Change of the full spectral distribution of the induced absorption coefficient of a PWO-II crystal after irradiation with an integral dose of 30Gy measured at room temperature. The spectra are measured 1 and 31 minutes after irradiation as well as after additional illumination for 10 and 160 minutes, respectively, with infrared light at 940nm.](image)

During the quality control of the radiation hardness of the PWO-II crystals an unexpected effect was observed at room temperature for the first time. After irradiation one recognizes besides the slow spontaneous recovery a significant additional acceleration of the change of the induced absorption coefficient $\Delta k$ by switching on an external light source. Figure 7 shows as an example the change over the entire investigated spectral range due to the illumination with infrared light (LED, $\lambda_{\text{max}}=940\text{nm}$) and indicates wavelength-selective effects. At the most relevant wavelength of 420nm the recovery develops with a time constant of $\tau=270\text{minutes}$. Similar measurements have been performed successfully even for pure or Mo-doped PWO samples or crystals of CMS/ECAL quality [7]. The stimulated recovery can be observed up to a wavelength of $\sim 1400\text{nm}$ but with increasing recovery times.

### 3.3. Stimulated recovery at low operating temperatures

More relevant for the PANDA-EMC application is the behavior at low temperature, which imposes a strong impact on all recovery mechanisms. Therefore, we have integrated into each detector module, comprising of a crystal and a photomultiplier as sensor, an additional set of four LEDs as light sources. The in total 10 identical detectors were prepared with crystals of different radiation hardness. To study the wavelength dependence of recovery LEDs with different colors were used. After cooling the modules down to T=−25°C the response to a low energy $^{60}$Co $\gamma$-source was measured before and after irradiation with 30Gy to determine the integral loss of light output. Illuminating afterwards with light of different wavelength, the recovery of the light loss was studied as a function of the integral illumination time up to two days.
Figure 8 shows the impressive results for the reduction of the relative light loss achieved with visible light sources centered at emission wavelengths of 470nm, 525nm, 640nm and 935nm, respectively. For blue light, nearly 90% of the original signal amplitude was restored already within the first 200 minutes. The used LEDs have imposed a photon flux of approx. $10^{16}$ photons/s. Presently, detailed studies and correlations with the crystal quality, the most efficient region of wavelengths, the required photon flux and the characterization of the recovered color centers via EPR measurements are under investigation. These results will provide a concept if the radiation damage during PANDA operation can be either compensated on-line without impact on signal readout or periodically after short shutdowns or breaks in an off-line mode. The concept and application of stimulated recovery is part of the patent TM 382_DE.

![Figure 8](image)

**Figure 8.** Recovery of the loss of the signal amplitude caused by irradiation as a function of the integral duration of illumination using different light sources. All detectors are operated at a temperature of $T=-25^\circ$C. The maximum light loss at the beginning reflects the radiation hardness of the individual crystals.

4. Conclusion
The final production of the PANDA-EMC has been started by the mass production of the crystals and confirms the excellent quality of the new generation of PWO-II. The delivered crystals meet the requirements to achieve sufficient resolution down to a few tens of MeV photon energy and to keep the response stable over the envisaged experimental periods of 6 months ensured in addition by the application of the stimulated recovery. Since the bialkali photocathode of the foreseen vacuum triodes is blind in the infrared region the external light can be even applied during the running experiment.

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