High-Energy Photon Detection With LYSO Crystals

M. Thiel, W. M. Döring, V. Dormenev, P. Drexler, *Member, IEEE*, R. W. Novotny, *Member, IEEE*, M. Rost, and A. Thomas

***Abstract*—For the first time, the response function to high-energy photons of a 3x3 matrix comprising large volume LYSO crystals was measured using energy marked photons provided by the tagged photon facility of MAMI. The crystal quality was determined based on the optical transparency, the intrinsic radioactivity and the luminescence yield. Energy and time resolutions for photons up to 490 MeV photon energy have been deduced from the reconstruction of the electromagnetic shower deposited into the crystal array and the data deliver very promising results.**

***Index Terms*—Calorimetry, detectors, radiation detectors, scintillation detectors.**

I. INTRODUCTION

FUTURE high-resolution homogeneous electromagnetic (EM) calorimeters will require fast, compact and radiation hard scintillator materials with high luminescence yield for optimum energy and time resolution as well as the capability to deal with high count-rates and multiplicities. $PbWO_4$ (PWO), which is presently used for the high resolution EM-calorimeters of the CMS/ECAL [1] and ALICE/PHOS [2] detectors at LHC (CERN) and is foreseen for the central calorimeter of the future PANDA [3] detector at FAIR (Darmstadt, Germany), meets most of the requirements but with limited light yield.

In the past years Ce-doped silicate based inorganic scintillator materials have been developed primarily for medical applications such as SPECT and PET tomography. Mass production of small samples but large quantities and the principal capability to grow also large size crystals have been established for oxy-orthosilicates as such Lu_2SiO_5 (LSO) and $Lu_{2(1-x)}Y_{2x}SiO_5$ (LYSO), both doped with cerium. The latter material combines high density ($\rho = 7.25$ g/cm^3), compact EM-shower containment (radiation length $X_o = 1.14$ cm, Moliére radius $R_M = 2.3$ cm) and fast response (decay time $\tau \sim 40$ ns at 420 nm). In addition, a light yield reported comparable to NaI(Tl) in case of small samples with optimized Ce-concentration would enable energy resolutions well beyond the capabilities of PWO. Similar previous studies have shown [4] that large volume LSO and LYSO crystals can be manufactured and appear to be radiation hard. Therefore, LYSO could be an attractive candidate material for future homogeneous EM-calorimeters, such as the discussed International Linear Collider [5] or the proposed super B factory [6].

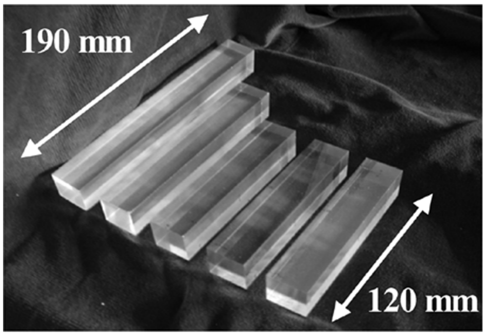

Fig. 1. Geometry of the investigated LYSO:Ce crystals, which were manufactured by the company Photonic Materials Ltd (UK).

II. THE LYSO TEST CRYSTALS

Ten large volume LYSO:Ce crystal samples, which were used in the present investigation, had been manufactured by *Photonic Materials Ltd.*, Bellshill (United Kingdom). Fig. 1 illustrates the crystals of rectangular shape with 25×25 mm^2 cross-section and a total length varying between 120 mm and 190 mm, respectively, with all surfaces being optically polished.

Natural lutetium contains the radioactive isotope ^{176}Lu with an abundance of 2.5%, which decays via β^- -emission into ^{176}Hf* with a half-life of 3.6 $\cdot 10^{10}$ years causing a typical intrinsic radioactivity of $\sim$ 500 Bq/cm^3. By means of an HPGe-detector the prominent decay photons of a rotational band in ^{176}Hf have been detected and identified [7]. Fig. 2 shows the calibrated γ -spectrum marking the specific decay photons of the rotational band built on the ground state.

A. The Optical Transmission

The longitudinal and transverse optical transmittance has been measured with a double beam monochromator in the relevant wavelength regime (Analytik Jena, Specord 200). Most of the crystals show a perfect longitudinal transmission close to the theoretical limits.

However, some samples indicate small inhomogeneities, which become visible in a slight variation of the transverse transmission when measured at several positions along the length of the sample. However, the variations stay well below 5% as indicated in Fig. 3. There are no indications for distinct absorption bands up to a wavelength of 700 nm.

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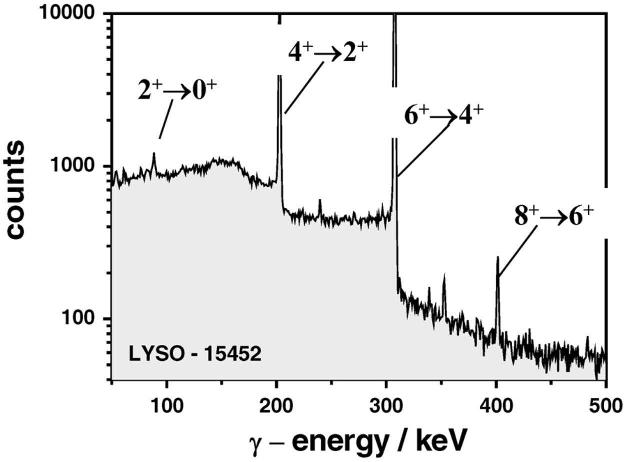

Fig. 2. Intrinsic γ -emission of a LYSO:Ce crystal measured with an HPGe detector. The prominent transition energies in ^{176}Hf are marked.

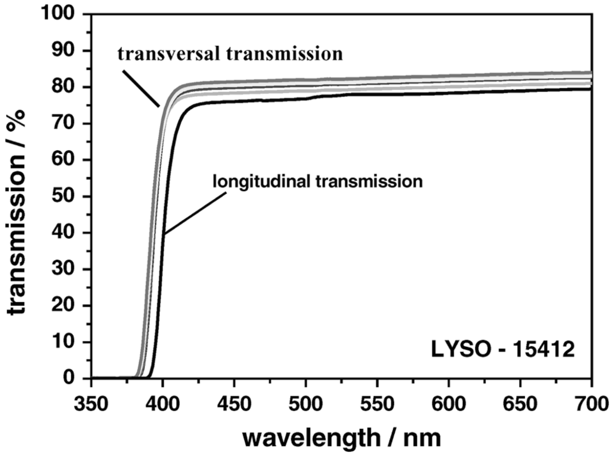

Fig. 3. Optical transverse and longitudinal transmission are shown for a slightly inhomogeneous crystal. The transversal measurement has been performed at different positions along the crystal axis.

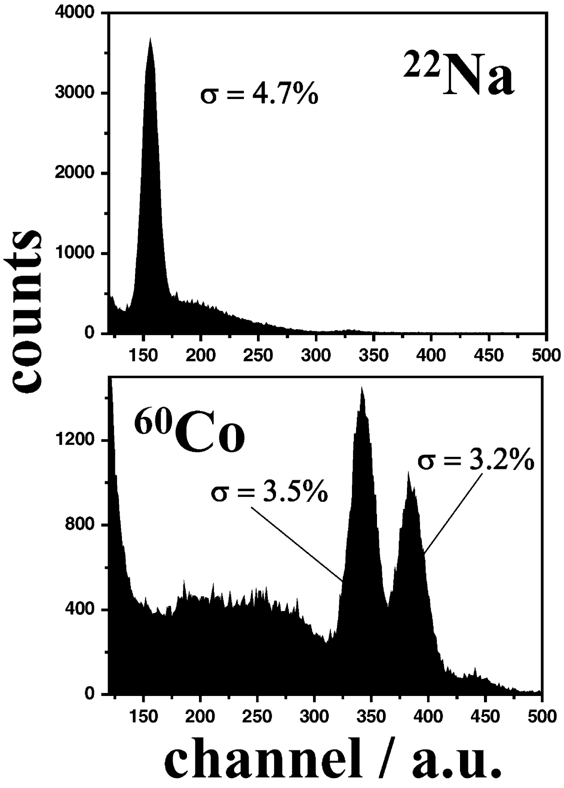

Fig. 4. Response functions of a typical LYSO:Ce crystal ($25 \times 25 \times 120$ mm^3) to low-energy γ -rays of the radioactive sources ^{22}Na and ^{60}Co, respectively.

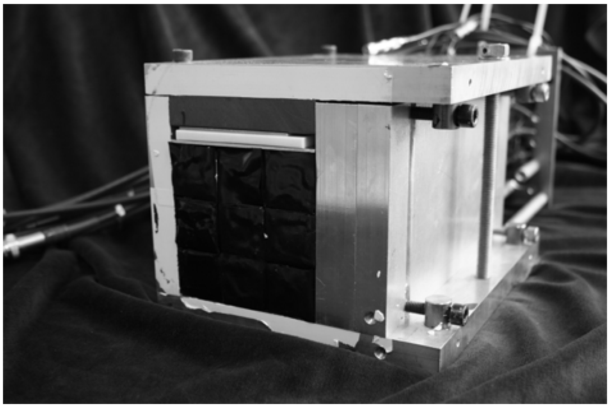

Fig. 5. Detector arrangement of the 3 × 3 crystal matrix (black) and the surrounding support structure, which allows an exact positioning of the central detector relative to the beam axis.

B. The Scintillation Yield

The light output has been determined by using low energy γ -sources. Due to the strong intrinsic radioactivity the measurement of the response function to photons relies on sources providing multiple photon emission such as ^{22}Na or ^{60}Co, respectively. The spectra shown in Fig. 4 are obtained by PHILIPS XP1911 photomultiplier read-out of the LYSO crystal and requiring coincidences with an additional BaF$_2$ scintillation detector in order to suppress the low energy photons (< 800 keV) emitted internally from ^{176}Hf*.

After calibrating the single photoelectron peak a total light output between 5600 and 7600 photons per MeV deposited energy, respectively, has been measured at the end face of the eight identical samples of 120mm length. The effective size and the quantum efficiency of the photo cathode have been taken into account. Additional measurements with a collimated source have indicated in some cases a significant inhomogeneity of the light yield along the crystal length, which cannot be explained by the observed differences in the optical transmission but could be addressed to a variation of the Ce-concentration. In general, the overall light yield, which is low compared to former reports, might be related to a not optimized cerium doping during the manufacturing process. However, lights yields in the same order of magnitude for large crystal samples have been reported as well in [8].

Detecting cosmic muons in a single detector shows an energy deposition of minimum ionizing particles of 10.5MeV per centimeter path length, based on the calibration with low energy photons.

III. RESPONSE FUNCTION TO HIGH-ENERGY PHOTONS

The reported experiment was performed with quasi-monochromatic photons delivered by the upgraded tagged photon facility at the electron accelerator MAMI at Mainz

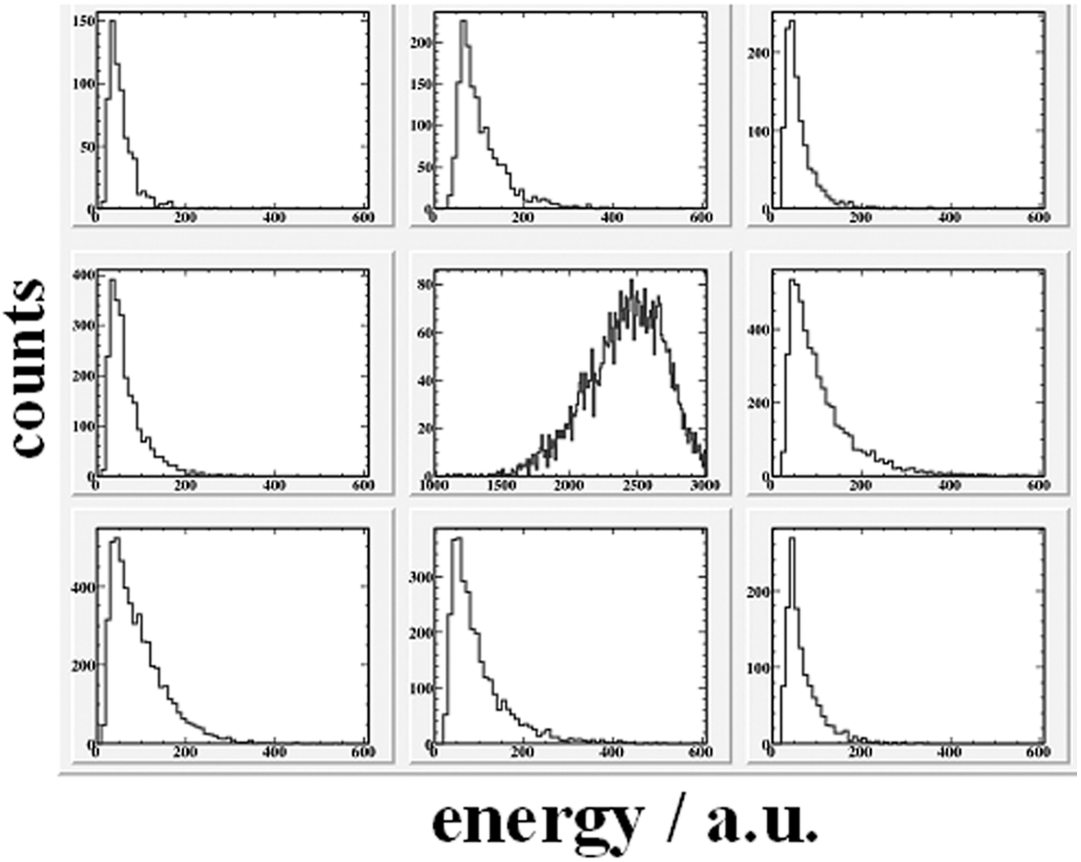

Fig. 6. Distribution of the electromagnetic shower measured with the 3 × 3 matrix at the highest incident photon energy of 493.8 MeV. The energy scales are shown in arbitrary units.

(Germany) exploiting the tagging of bremsstrahlung produced by a monoenergetic electron beam ($E_e = 570$ MeV). After bremsstrahlung emission the momenta of the decelerated electrons were analyzed in the magnetic spectrometer of the Glasgow-Mainz tagger [9], requiring a time coincidence of the detected bremsstrahlung photon with the corresponding electron identified in the focal plane. The typical energy width per tagging channel is $\Delta E \sim 2.0$ MeV. Fifteen photon energies in the range between 179 MeV and 494 MeV, respectively, were chosen. The LYSO-array was located at a position 12 m downstream from the radiator. A set of collimators limited the beam spot to a diameter of $d < 8$ mm at the front face of the crystals.

The detector matrix, which was temperature stabilized at 18°C consisted of an array of 3×3 rectangular crystals of 25×25 mm^2 cross section. All crystals were 120 mm long except the larger central module, which had a length of 190 mm. The crystals were individually wrapped in TEFLON foil, coupled with optical grease (BAYSILONE 300.000) to photomultiplier tubes (Hamamatsu R4125) and covered light-tight by a thin shrink tube. The detector matrix could be moved remote controlled in two dimensions perpendicular to the axis of the collimated photon beam by stepping-motors, to perform a relative calibration of each detector element with the direct photon beam.

In order to allow the remote control moving of the detector array and to ensure a temperature stabilization, the matrix was put in a cooled, closed system. Fig. 5 shows the support structure, which locks the crystals into position and allows an accurate positioning of the whole array in the photon beam.

The photomultiplier output of each module was digitized by means of a charge-sensitive ADC. A fast constant-fraction timing signal was deduced to determine the response time relative to the central module. Both information were only digitized (CAEN V874B) in case of a coincidence of the central calorimeter module with one of the timing signals of the selected tagger channels and finally recorded event-by-event for an off-line analysis.

A. The Shower Reconstruction

The distribution of the electromagnetic shower within the 3x3 crystal matrix has been obtained after a careful relative calibration of the individual modules. The low energy threshold amounts to approx. 4.5 MeV for each matrix component. Fig. 6 illustrates for the highest incident photon energy of 493.4MeV the energy distribution into the individual modules of the array. The energy scale is given in arbitrary units.

B. The Deduced Line Shape and Energy Resolutions

Based on the relative energy calibration the total energy has been reconstructed by summing up event-wise all responding

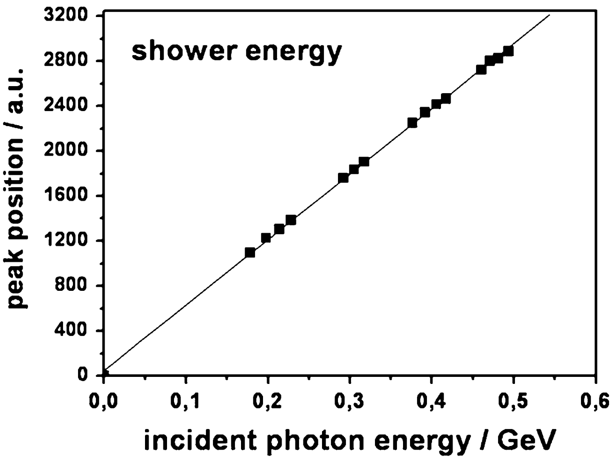

Fig. 7. Peak position of the shower energy in arbitrary units is plotted versus the incident photon energy in GeV. The figure highlights the linearity over the whole energy range with a correlation coefficient of 0.9998.

modules. The response of the central module as well as the integrated sum of the 3 × 3 matrix show a perfect linear correlation with the incident photon energy over the investigated energy regime as illustrated in Fig. 7.

For the highest and lowest photon energies the components of the reconstruction of the line shape, the response of the central module, the sum of the neighboring units and the resulting total deposited energy are shown in Fig. 8.

The overall response can not be well characterized by a Gaussian lineshape, primarily due to the relatively high low energy threshold in the outer crystals ($\mathrm{E}_{\mathrm{thr}} \sim 4.5$ MeV) and significant shower leakage caused by the limited length of the crystals.

Nevertheless, the overall energy resolution, which is summarized in Fig. 9, documents the high light yield leading to a small statistical term. In contrast, the shower leakage is reflected by the large constant term.

C. Time Resolution

As a first estimate, the relative timing between the central detector and one of its neighbors has been analyzed. In spite of the large difference in signal amplitude, a nearly Gaussian distribution has been deduced. Assuming similar resolution of both detector modules, an individual time resolution of $\sigma_t \sim$ 150 ps can be obtained by dividing the measured width by a factor $\sqrt{2}$.

D. Monte-Carlo Simulation

Further investigations were done using GEANT4.80 Monte-Carlo simulations. In addition to the pure GEANT features the exact crystal geometry and the reflector material in between were included. In addition, the relatively high experimental thresholds of 4.5 MeV were taken into account. The results are shown in Fig. 11. The statistical term is in the same order as that obtained from the experimental data. The difference can be addressed to the photon statistics and light collection efficiency, which are not included in the simulation. The constant terms differ by almost a factor 2. One explanation can be the inhomogeneity of some of the crystals, as was described in the previous section. In addition, it is known, that the lateral shower distribution delivered by GEANT appears significantly narrower compared to experimental data. Therefore, lateral shower leakage might be underestimated.

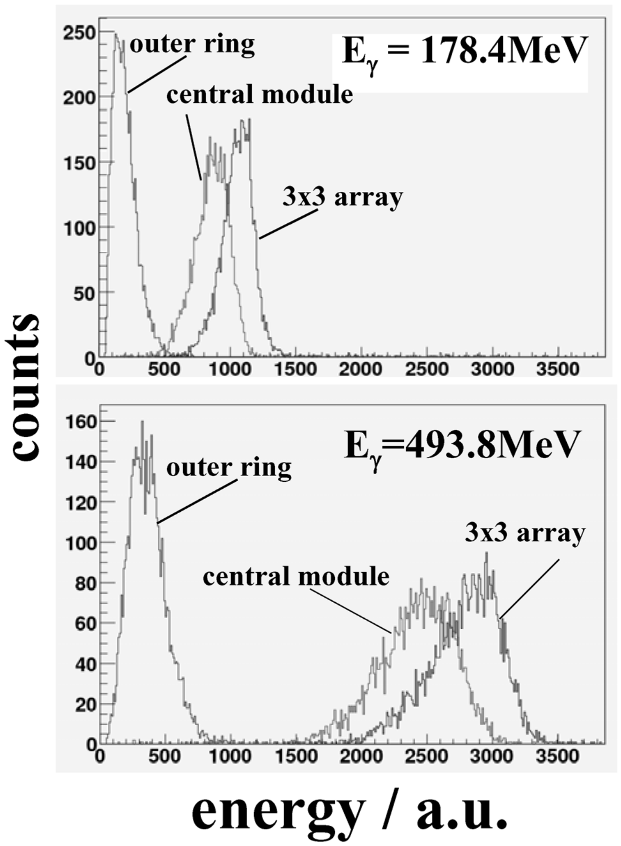

Fig. 8. Reconstructed line shape of the response function of the 3 × 3 matrix to photons is shown for the two extreme incident energies of 178.4 MeV and 493.8 MeV, respectively. The figure illustrates the response of the central module, of the surrounding ring and the total matrix.

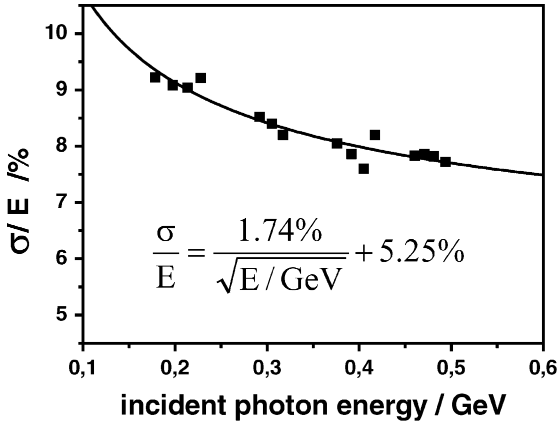

Fig. 9. Energy resolution of the 3 × 3 LYSO matrix measured for high-energy photons up to 500 MeV. The deduced parameterization is indicated.

IV. CONCLUSIONS AND OUTLOOK

For the first time, a 3 × 3 matrix of large size LYSO crystals has been used to determine the response function to high-energy photons. The quality of some samples reaches already good

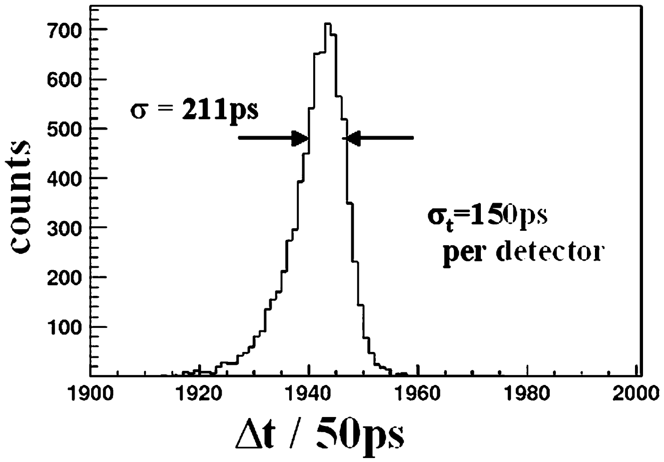

Fig. 10. Spectrum illustrates the typical time resolution of the individual LYSO modules read-out with photomultipliers. The distribution represents the relative time between the central module and one of its direct neighbors.

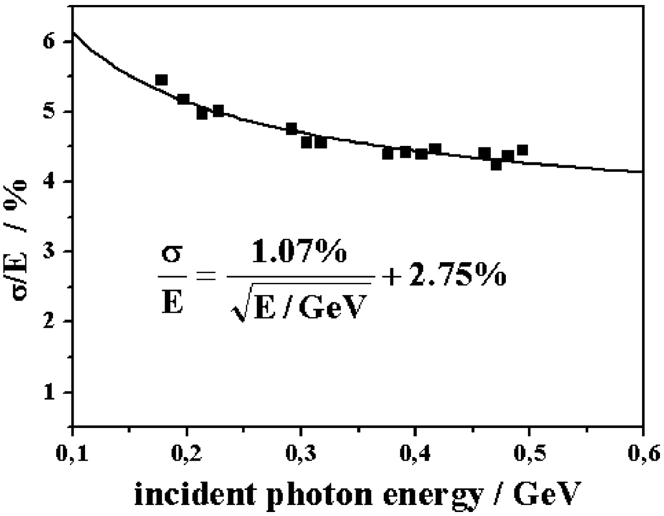

Fig. 11. Monte-Carlo Simulation of the energy resolution of a 3 × 3 LYSO-crystal array performed with GEANT4.80.

optical transparency and homogeneity as well as provides sufficient luminescence yield to achieve attractive energy resolutions for low energy γ -rays.

The first attempt to contain and reconstruct the electromagnetic shower initiated by monoenergetic photons up to $\sim$ 500 MeV energy delivers very promising results. In spite of a significant shower leakage due to the limited crystal size, the deduced energy resolution yields a small statistical term in the parameterization over the investigated energy regime. The achieved time resolution of 150 ps reflects the fast response function of the scintillator material and allows experiments at high count-rates as well as time-of-flight techniques.

However, applications in medium and high-energy calorimetry will require module sizes up to 25 radiation lengths and a homogeneous and further increased light yield in order to fully exploit the performance already observed for small samples. In particular, the technology for mass production of large crystals has to be established.

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