Development of a novel high granularity crystal electromagnetic calorimeter

Baohua Qi[1,2,*], *Fangyi* Guo[1], *Yong* Liu[1,2,**], and *Zhiyu* Zhao[3,4]

[1]Institute of High Energy Physics, Chinese Academy of Sciences. Yuquan Road 19B, 100049 Beijing, China
[2]University of Chinese Academy of Sciences. Yuquan Road 19A, 100049 Beijing, China
[3]Tsung-Dao Lee Institute, Shanghai Jiao Tong University. 520 Shengrong Road, 201210 Shanghai, China
[4]ShanghaiJiao Tong University. 800 Dongchuan Road, 200240 Shanghai, China

Abstract. The high-granularity crystal calorimeter has been proposed for future lepton colliders with an excellent electromagnetic energy resolution. To evaluate the crystal ECAL performance and validate the design specifications from individual units to the entire detector, extensive R&D activities have been performed. Geometry design along with dedicated software development is currently ongoing. Hardware experiments in both laboratory and beam facilities have been conducted, providing reliable data for the crystal ECAL design.

1 Introduction

Motivated by the physics programs of precision measurements of the Higgs, W/Z bosons, and the top quark, the detector systems for future lepton colliders, e.g. the Circular Electron Positron Collider (CEPC)[1], have stringent requirements on their calorimeters to achieve unprecedented jet energy resolutions. As part of CEPC's "4th detector concept", a novel high-granularity crystal electromagnetic calorimeter (ECAL)[2] has been proposed, with an optimal electromagnetic (EM) resolution of $2-3\,\%/\sqrt{E(\mathrm{GeV})}$ and sufficiently low detection limit of photons with the homogeneous structure. Utilising the Particle Flow Algorithm (PFA) with other optimised sub-detectors, the new ECAL design concept is expected to improve the Boson Mass Resolution (BMR) from 4% with the CEPC baseline detector to 3% level.

Significant R&D efforts have been made for this crystal ECAL, to evaluate the design specs from sensitive units to the whole detector. The physics potentials of the crystal calorimeter concept were studied with a full detector geometry. Geant4 full simulations have been conducted to assess the impact of light yield, threshold, extra materials, time response, etc. Laboratory measurements with characterisations of crystal, silicon photo-multipliers (SiPMs), and readout electronics have been carried out to validate the simulations and demonstrate the feasibility of the hardware. A small-scale crystal module has been developed and tested under beam conditions for performance studies and system-level investigations.

With the new CEPCSW[3] software framework, the dedicated particle-flow algorithm for crystal ECAL has been developed and is under optimising, targeting significant improvements in the separation of close-by showers and jet reconstruction performance.

In this context, the latest R&D progress of the novel high-granularity crystal ECAL will be elaborated, including the general design, lab characterisations and beamtest studies.

2 Crystal ECAL design

As illustrated in Figure 1, the crystal ECAL tower is constructed from $1\times1\times40\ \mathrm{cm}^3$ long crystal bars. Within each layer, the crystal bars are arranged in parallel, while two adjacent layers are oriented orthogonally. This arrangement facilitates position reconstruction by combining the information obtained from the neighbouring layers. The design can realise maximum longitudinal segmentation, minimum inactive materials between layers and a significant reduction in readout channels. Each crystal bar is read out by two silicon photo-multipliers (SiPMs) at two ends, which can also provide timing information for positioning reconstruction and clustering. The major challenges are sophisticated software for this design, pressure on pattern recognition for clustering and difficulties in mechanical designs. Currently, the dedicated software has been preliminary developed, resolving the basic issues in the reconstruction process. The geometry design is also gradually progressing. The first barrel and endcap ECAL design are shown in Figure 2. The ECAL thickness is designed to be equivalent to approximately 24 radiation lengths (X_0). In the barrel section, there are 480 towers distributed across 15 rings, while the endcaps feature 117 towers each. Cylindrical barrel featuring alternately arranged trapezoidal towers, designed to prevent cracks from directing toward the interaction point (IP). Disc-shaped endcaps are composed of square towers. In total, the CEPC crystal ECAL will utilise around 720k crystals.

*e-mail: qibh@ihep.ac.cn
**Corresponding author. e-mail: liuyong@ihep.ac.cn

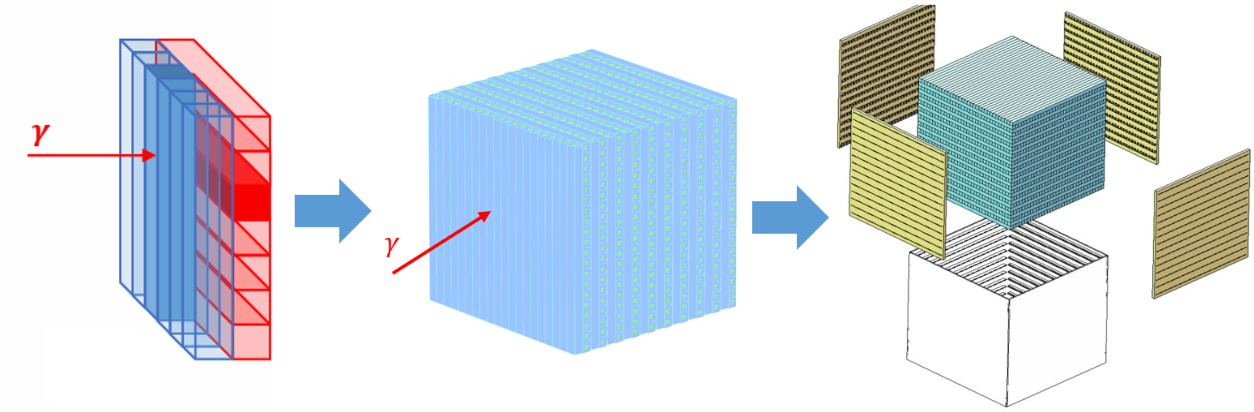

Figure 1. Design of the crystal ECAL tower. 40 cm long crystals are arranged orthogonally between adjacent layers to achieve high granularity. Photon sensors are placed on four sides of the tower.

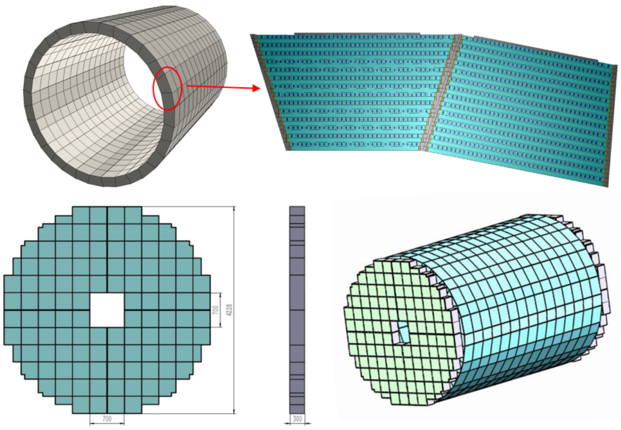

Figure 2. Preliminary geometry design of the crystal ECAL, featuring trapezoidal barrel towers and square endcap towers.

3 Characterisations of crystals and SiPMs

The preliminary design specifications of the crystal ECAL are listed in Table 1. The detector requires moderate light yield, good crystal uniformity, optimal time resolution and large dynamic range. To evaluate the hardware-level feasibility, a set of lab measurements of crystals and SiPMs has been conducted:

- SiPM response linearity test. Hamamatsu SiPMs with 10 μm pixel pitch and 3×3 mm^2 active area (around 90k pixels) have been tested with laser. The non-linear response curves have been obtained. Considering the light decay time of the crystal, the preliminary result shows, that the pressure on the SiPM dynamic range is lower than expected with relatively slow decay time crystal candidates, due to the SiPM pixel recovery effects. In summary, the application of SiPM with a high pixel density is expected to enable the detection of more than 10^5 photons.
- Uniformity scan of long crystal bar. Radioactive source test with 40 cm BGO crystals shows generally good uniformity at about 2.5% level along a single bar, as shown in Figure 3.
- Time resolution measurements. Radioactive source tests, cosmic-ray tests as well as beamtests have been conducted. With a single 40 cm BGO bar readout from two sides, the time resolution has been measured to be 4 ns at 662 keV, 1.5 ns for Minimum Ionising Particle (MIP) signals. The best result is about 200 ps with shower signals larger than 12 MIPs.
- Dynamic range tests of electronics. The new commercially available 32-channel ASIC MPT2321 with a large dynamic range has been first tested with LYSO crystals and electron beam. The experiment result shows the chip features a high signal-to-noise ratio for the SiPM single-photon calibration and a large dynamic range of detecting approximately 33,000 photons.

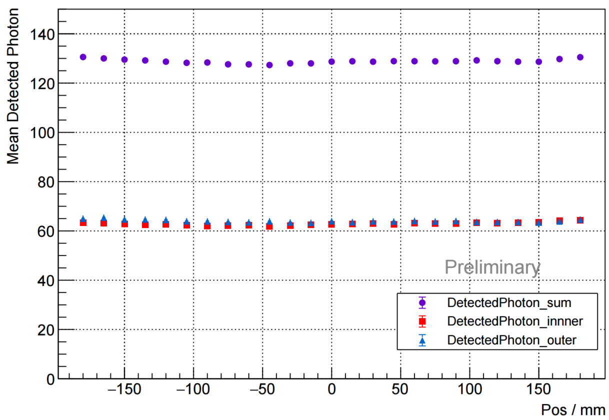

Figure 3. Response uniformity along a 40 cm BGO crystal bar. Readout from two sides of the crystal.

4 Crystal module design and beamtests

To identify critical issues on the system level (e.g. mechanical design, PCB, electronics), and further evalu-

Table 1. Key specifications for the crystal ECAL.

Parameters	Value/Range	Remarks
MIP light yield	200 p.e./MIP	Crystals of unit length
Dynamic range	$1 - 4.5 \times 10^5$ p.e. per channel	Deposited energy up to 40 GeV per crystal bar
Energy threshold	≤ 0.1 MIP per channel	Depends on noise level
Timing resolution	400 ps @ 1 MIP	Ideal value from Geant4 simulation
Crystal uniformity	$\leq 1\%$	Calibration precision
Temperature stability	Stable at 0.05 Celsius	Reference from CMS ECAL

ate the EM performance of the crystal ECAL, a small-scale crystal module has been designed and produced for beamtests. As shown in Figure 4, BGO crystals with $2 \times 2 \times 12$ cm^3 dimensions have been used in the module. Each layer consists of 6 crystals, with adjacent layers oriented orthogonally. Due to the limited load-bearing capacity of the PCB, a customised PCB design was produced, with 3D-printed support structures traversing the PCB, providing structural reinforcement for the crystals. Besides, all of the crystals have been tested with the radioactive source for light yield calibrations.

Two beamtests at the CERN T9 and the DESY TB22 beamlines were conducted. The CERN beamtest utilised a crystal module with 10.7 X_0 thickness for commissioning and the first parasitic test. Data taking with the muon beam was successfully finished, and the crystal module has been confirmed to function properly. The DESY beamtest employed a crystal module with twice thickness (21.4 X_0), and two 1 cm^3 plastic scintillators for beam collimation. The setup is shown in Figure 5. Due to the considerable uncertainty in beam momentum, and lack of muon calibration for the crystal module, the resulting energy resolution is depicted in Figure 6. Here a momentum spread of 1% is assumed, the anticipated energy resolution from the Geant4 simulation is much better than that from the beam data. The impact of beam momentum spread is particularly significant in this context.

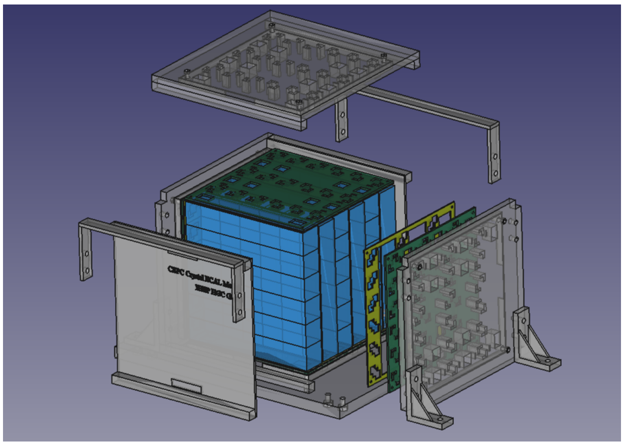

Figure 4. Design of the crystal module with 10.7 X_0 thickness. 36 BGO crystal bars are shown in blue, while SiPM PCBs, encompassing four sides, are represented in green. The remaining parts are 3D-printed support structures.

Figure 5. Crystal module beamtest setup at DESY.

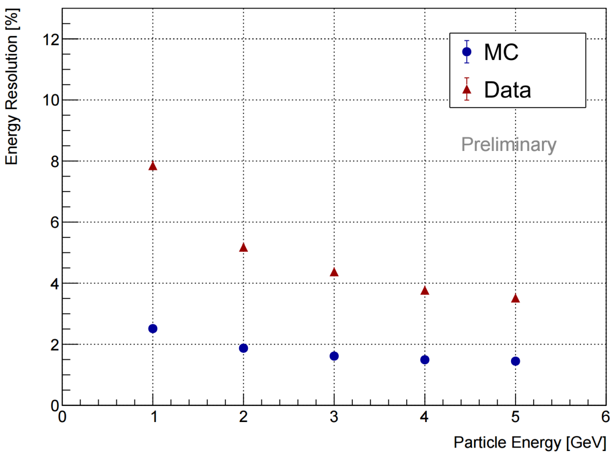

Figure 6. Electron energy resolution of the 21.4 X_0 crystal ECAL module. Measured at DESY TB22 beamline.

5 Summary and outlook

The high-granularity crystal calorimeter is a promising candidate for future high-energy collider experiments with a superior EM energy resolution and PFA capability. Extensive hardware R&D activities have been completed to address key questions of the detector requirements. Experiments with crystals and SiPMs have been carried out for the characterisation of detector units. A small-scale crystal module has been developed, and two beamtests have been conducted to evaluate its performance. The next beam experiment is planned to be conducted again at CERN to further investigate the EM energy resolution of the crystal module. Additionally, features such as a temperature control system will be incorporated.

References

[1] The CEPC Study Group, CEPC Conceptual Design Report Volume II - Physics & Detector. https://arxiv.org/abs/1811.10545

[2] Baohua Qi, R&D of a Novel High Granularity Crystal Electromagnetic Calorimeter. Instruments **6**, 40 (2022). https://doi.org/10.3390/instruments6030040

[3] CEPCSW (CEPC offline software prototype based on Key4hep). https://github.com/cepc/CEPCSW