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Development of a Novel Crystal Electromagnetic Calorimeter and Particle Flow Algorithm for Future Lepton Collider Experiments

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A novel high granularity crystal electromagnetic calorimeter design is proposed for the future lepton collider experiments, to meet the stringent requirement on the jet measurement and achieve optimal EM resolution of $3\%/\sqrt{E}$ and high efficiency for low energy photons. R&D efforts have been undertaken in crystal characterization, silicon-photomultipliers (SiPM) and multi-channel readout electronics. A small-scale crystal module is developed and tested in beam for the system-level validation. At the full detector level, a novel PFA has been developed and its performance has been validated in the full simulation of 2-jet events in CEPC. The pattern recognition concepts introduced in this PFA could potentially be considered for the reconstruction of other homogeneous ECALs.

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1. Introduction

After the discovery of Higgs boson by ATLAS and CMS experiments in Large Hadron Collider (LHC) [1, 2], several next generation lepton collider experiments are proposed to perform precise measurements of Higgs boson and other Standard Model (SM) particles, as well as provide valuable opportunities to explore the new physics beyond the SM. These experiments raise stringent requirements on the detection precision of jets. The Particle Flow Approach (PFA) proposed at LEP period is a promising solution towards this measurement. In the last decades the CALICE collaboration has developed the high granularity electromagnetic and hadronic calorimeters (ECAL and HCAL) for the International Linear Collider (ILC) project. To match the requirement of compact shower structure and high granularity requirement in PFA, the ECAL and HCAL in CALICE design adopt the sampling structure, with silicon/scintillator/gaseous units as active material and tungsten/steel as absorber. The overall performance for jet is ensured by PFA, but the intrinsic energy resolution remains constrained, comparing with the homogeneous calorimeter.

In response to this issue, we proposed a novel crystal ECAL and undertook the R&D under Circular Electron Positron Collider (CEPC) project. Scintillate crystal, as BGO can ensure a sufficient intrinsic energy resolution from its bright scintillation light. Through the orthogonal arrangement of crystal bars in different layer the high granularity structure required by PFA can be also satisfied. The global detector design is detailed in Sec. 2. Preliminary experimental results and some considerations about the construction are presented in Sec. 3. The shower overlap in homogeneous crystal and the special crystal bar structure makes the traditional particle flow algorithms, e.g. PandoraPFA un-adaptable. Thus we developed a dedicated PFA to solve the specific issues. A brief description of the algorithm and the performance are shown in Sec. 4. Finally the summary and prospects are discussed in Sec. 5.

2. Conceptual design of BGO bar ECAL in CEPC

As a homogeneous calorimeter, the material budget of insensitive structures must be strictly constrained. This necessity conflicts with the traditional high granularity calorimeter, in which the sensitive silicon sensor or scintillator strip are designed as individual readout units and mechanical components are incorporated within the absorber. To address this issue, we designed a novel detector layout. The structure of one functional module is shown in Figure 1. The crystal bars sized $1 \times 1 \times 40$ cm^3 are arranged to be orthogonal to each other in adjacent layers. Scintillation light is collected by two SiPMs positioned at the ends of crystal bar. This configuration minimizes inactive material between layers, reduces readout channels, and simultaneously preserves 3D information through cross-location analysis of adjacent crystal layers The total depth of one module is 24 X_0, with 28 layers for longitudinal granularity. The EM resolution is expected to be $< 3\%/\sqrt{E} \oplus 1\%$, and the PFA performance can be maintained after the reconstruction.

As one major component of the CEPC detector, the global structure of the crystal bar ECAL barrel is polygon with 32 sides, with inner radius 1830 mm, depth 300 mm and half length 2900 mm, covering $|cos\theta| < 0.85$ range. An inverted trapezoid structure is designed for adjacent modules to avoid the direct leakage from interaction point. Crystal bars with varies length, from 288 to 409 mm are placed orthogonally as mentioned above. Inactive material such as SiPM, frontend electronic board, cooling copper and carbon fiber supporting are considered. The geometry model is constructed with DD4HEP for simulation within CEPCSW, the CEPC software framework based on Key4HEP. The full barrel detector, including a silicon vertex detector, a silicon strip inner tracker, a timing projection chamber and a scintillation glass tile HCAL barrel are used for the PFA physical performance studies.

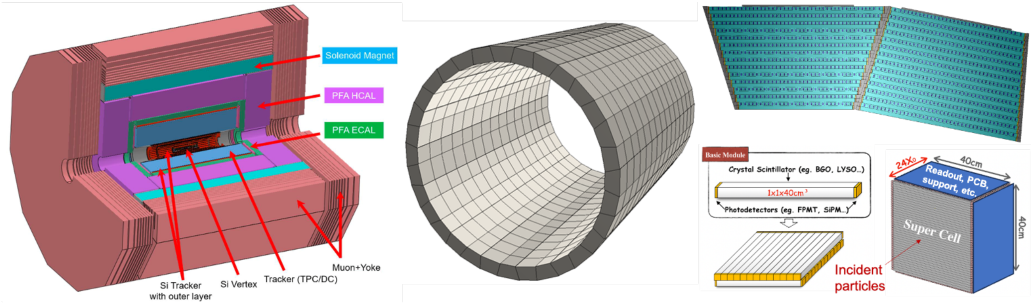


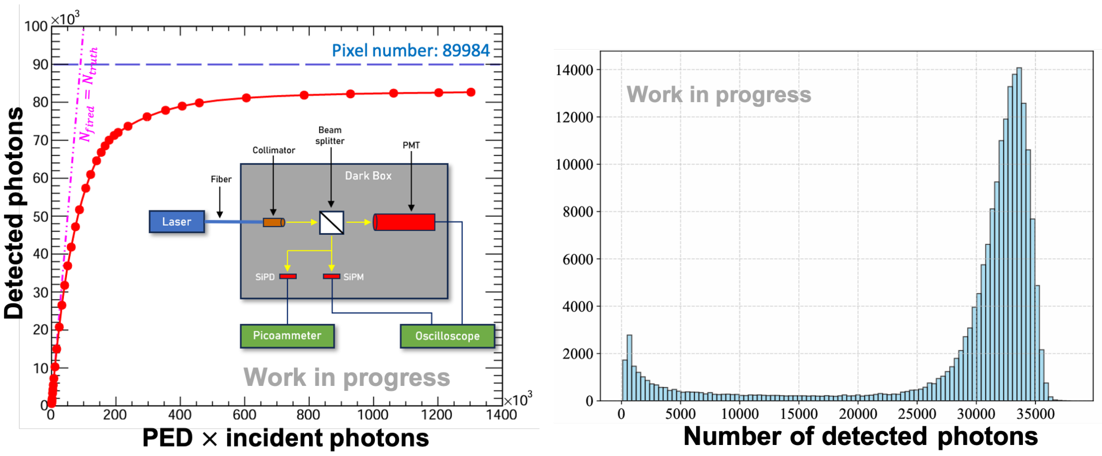
Figure 1: Left: global CEPC detector design. Middle: 32-side polygonal ECAL. Right: inverted trapenzoid module and the module structures of crystal bars with two-ended readouts.

3. Characterisations of units

The intrinsic EM energy resolution, as well as the requirement on the crystal uniformity were studied and discussed in [3] and [4]. With the intrinsic light yield of 8200 photon / MeV for the BGO, the desired detected light yield 200 p.e./MIP from end-side SiPM can be ensured both from optical simulation and cosmic ray test. The uniformity along a single bar has been tested to be within 2.5%. A calibration system for the future CEPC detector is under consideration, to control this non-uniformity within 1%.

The most energetic EM object in CEPC environment is the 180 GeV Bhabha electrons in $t\bar{t}$ operation mode, $\sqrt{s}$ = 360 GeV, The maximum energy deposition in one bar is estimated from the full detector simulation to be below 30 GeV. This determines the dynamic range requirement of SiPM and electronics from 0.1 to 3300 MIPs. The SiPM with 3×3 mm size and 10 μm pixel pitch (HPK S14160-3010PS) was chosen and tested with the pico-second laser as light source, using a PMT for calibration. Results shows a good linearity from 1 to 10^4 p.e. detected in SiPM as shown in Fig. 2(a) [5]. For larger range this response curve could provide the correction for SiPM saturation effects. Such 3×10^5 dynamic range requirement raises stringent pressure to the electronics system design. The novel high-precision multi-channel Application-Specific Integrated Circuit (ASIC) MPT2321-B developed by MicroParity could be a promising candidate. Lab test with LED and SiPM proves its capability of single photon signal detection, and a 33000 p.e. signal from electron beam response in LYSO can also be covered 2(b). Considering the 7×10^5 gain of used SiPM, this corresponds to a 3.7 nC charge tolerance.

The timing information can provide a new dimension for the shower reconstruction, e.g. separating the fast and slow component in hadronic showers, or removing the pileup in high luminosity colliders. In this crystal bar ECAL design, the time difference from 2 ends of crystal bar can contribute in locating the shower along the bar. This feasibility is tested with electron beam



(a) (b)

Figure 2: Left: SiPM linear range test with laser and PMT. Right: Detected charge (calibrated to photon number) in MPT2321-B from LYSO in electron beam environment.

in 40 cm and 60 cm BGO bars. Waveform signals from SiPM were readout with high frequency oscilloscope (1.25 GS/s) and the time information is obtained from the waveform leading edge fitting. Several pre-shower BGO crystals are placed at the front of tested BGO bar to obtain the time resolution at different signal amplitude in Fig. 3. At the best case, a 200 ps time resolution with enough (>12 MIP) signal can be measured, and generally does not change with the shower position. This result is partially limited by the response of electronics. More detailed studies need to be performed.

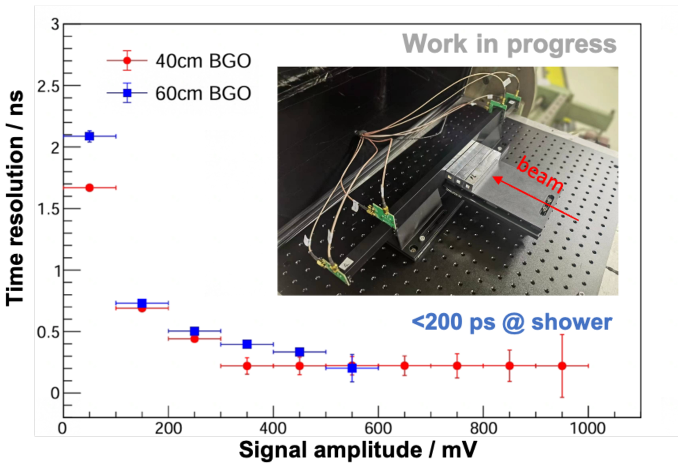


Figure 3: Measured time resolution in 40 cm and 60 cm BGO bars, with different signal amplitude.

3.1 Other items

To become a complete detector design for the future collider, many other aspects need to be demonstrated and is now under consideration. Among them temperature variations, cooling service, supporting mechanical structure, crystal - SiPM coupling, radiation tolerance, as well as calibration system design are studied. These topics is expected to be firstly studied with simulation model, and then tested within the timeline of CEPC project. Currently a small scale crystal module with size of $12 \times 12 \times 24\ cm^3$ has been developed and tested with electron and muon beam in DESY TB22 and CERN T9 [4]. Data analysis is still ongoing.

4. Dedicated PFA reconstruction algorithm

The traditional particle flow concept imposes demands on both detector design and reconstruction algorithms. The fundamental idea is to distinguish the showers generated by different particles. This necessitates that the calorimeter has a compact structure, a small Molière radius, and both transverse and longitudinal segmentation. Subsequently, reconstruction algorithms, such as PandoraPFA [6], can effectively perform this pattern recognition task. However, the homogeneous material in a crystal ECAL challenges the compact structure requirement. With superior energy measurement, energetic showers can be identified from the central core by employing advanced algorithms. The required high granularity 3D structure is achieved through the use of 2D orthogonally arranged bars. However, reconstructing this information into 3D may introduce “ghost hits” due to mismatches. In a Higgs factory with $\sqrt{s}$=240 GeV, where the typical jet energy ranges from 50 to 100 GeV, a $40 \times 40\ cm^2$ module exacerbates this issue. This motivated us to develop a dedicated PF algorithm for this crystal bar ECAL.

The algorithm is primarily divided into four steps. In the first step, neighboring fired crystal bars and HCAL hits are clustered together. Local maxima are identified among these clusters, and tracks from the inner tracker are incorporated into the framework and extrapolated to the calorimeter. In the second step, showers are recognized by clustering the local maxima, which are then merged based on specific topological conditions; these are regarded as the shower core. In the third step, clusters containing multiple cores are split according to predicted shower profiles. Ghost hits are vetoed by utilizing timing information, neighboring showers, and extrapolated track points. Finally, HCAL clusters are merged with adjacent ECAL clusters and linked to relevant tracks, as done in other PFAs, with an energy-momentum matching applied to the clusters and tracks.

The performance of this PFA is validated in physical process reconstruction, $e^+e^- \rightarrow ZH \rightarrow \nu\nu gg$, $\sqrt{s}$ = 240 GeV. All visible objects in this final state are summed over, and a clear Higgs mass of m_{vis} = 127.3 ± 5.23 GeV can be obtained in full CEPC barrel detector reconstruction (events with forward jets are vetoed from truth information) as shown in Fig. 4. Considering there are visible track fragments in current track reconstruction, the Higgs mass resolution can be further improved to 4.74 GeV by using the truth tracks as input of PFA.

5. Summary and prospects

In this proceeding we presented a new concept of PF ECAL for future lepton collider experiments, including the hardware activities in long BGO crystal uniformity, dynamic range of SiPM and electronics system, timing capability, and a dedicated PF reconstruction algorithm development. The boson mass resolution is expected to be controlled within 4% in CEPC. In this design the

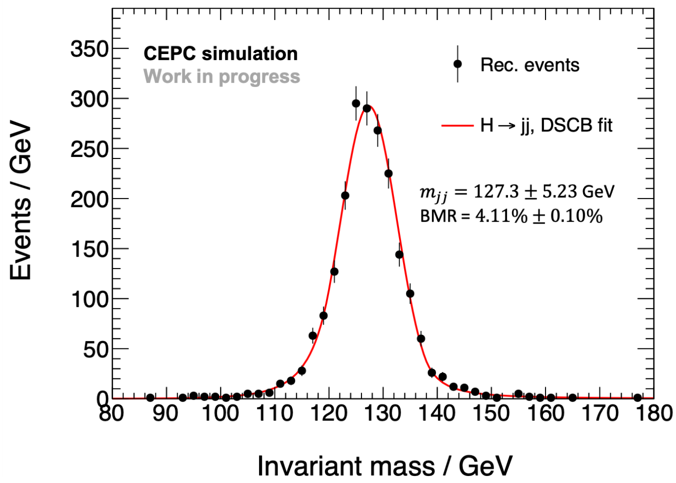


Figure 4: Reconstructed invariant mass distribution in $H \rightarrow gg$ process.

software compromises the shortcomings of crystal and highlights its energy resolution, breaking the traditional requirement of PF calorimeter. More detailed studies are still ongoing.

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