Design and Simulation of a Stereo Crystal Electromagnetic Calorimeter for the CEPC

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Abstract. In this paper, we present the design and simulation of a Stereo Crystal Electromagnetic Calorimeter (SCECal) for the Circular Electron Positron Collider (CEPC). The SCECal is based on a novel stereo crystal configuration that obtain the 3D position resolution of the calorimeter from 2D readout. We analyze the performance of the SCECal using simulations with BGO crystals and evaluate the energy and 3D positioning resolution for different types of particles. Additionally, we investigate the separation power between photons and pions using a simplified reconstruction method. The results show promising energy and position resolution as well as efficient particle separation capabilities.

1 Introduction

The CEPC [1] requires advanced calorimetry solutions to meet its physics goals, such as precision Higgs and electroweak measurements. The Particle Flow Algorithm (PFA) [2] based calorimeter is an option for achieving good shower separation and energy resolution. A calorimeter with good energy resolution, shower separation, and position resolution to accurately measure the particles produced in high-energy collisions is then mandatory. Several technical options are available for CEPC ECal, including silicon-tungsten, scintillator sampling, dual readout, and homogenous crystal designs. Among these, the Stereo Crystal ECal is proposed to address the challenges associated with traditional long-bar crystal ECals. We present the analytical optimization of the SCECal geometry, the simulation performance of the SCECal using BGO crystals as work principal demonstration.

2 The Design of Stereo ECal

2.1 Traditional Crystal ECal vs. Stereo Crystal ECal

Traditional crystal ECals like those used in CMS [3] experiments have long crystal bars pointing to the beam interaction point (IP), with slight twists to prevent particle escape. They have fine segmentation on the polar and azimuth angle directions, while only one segmentation along the radius (R). The proposed Stereo Crystal ECal, however, features crystal bars not pointing directly to the IP. They are transversal to the direction of the beam and have a pointing angle α with respect to the detector radius.

2.2 Geometry of Stereo Crystal ECal

The design is done using a cylinder coordinates, with Z axis along the beam directions. This design allows for multiple sampling points along the radius (R), optimized for single-end readout on the outer surface relative to the IP, creating a circular structure with trapezoidal crystals bars. To enhance position resolution along R and resolve the bias along azimuth angle introduced by the pointing angle, even layers and odd layers along Z have opposite sign of pointing angle. **Figure 1** shows the design of stereo crystal ECal.

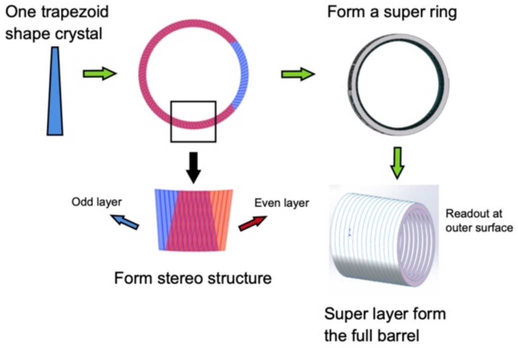

Figure 1: Illustration of construct the structure of Stereo Crystal ECal. Trapezoid shaped crystals form a stereo ECal ring, the ECal super ring, and the whole barrel.

The design of the Stereo Crystal Electromagnetic Calorimeter (ECal) involves three degrees of freedom for a given inner and outer radius of the barrel section:

1) Pointing Angle (α):

The angle at which the crystal bars are oriented relative to the detector radius. This angle typically

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ranges between $-\pi/2$ and $\pi/2$ (the sign of the angle indicates the crystals pointing to clockwise or counterclockwise w.r.t. radius). It is correlated with the crystal length L_R

2) Number of Sampling Layers along R (N_R):

The total number of crystal layers along the radius. The number of layers affects the granularity and, consequently, the resolution of the calorimeter along R. It is correlated with the crystal size (typically ~1cm) along azimuth angle (L_ϕ)

3) Crystal Size along the Z-axis (L_Z):

The size of the crystals along the Z-axis. Typically, it is about 1 cm.

These 3 parameters allow for the optimization of the ECal's geometry to enhance its performance in terms of energy resolution and particle separation. If we choose a typical size of crystal along Z-axis and along azimuth angle, the design only has one degree of freedom left, either the pointing angle, or the Sampling Layers along R(N_R). This simplifies the overall optimization of the design a lot. By comparing N_R=7, 10, 14 configuration, with compromise of the segmentation along radius and minimize number of lighted crystals for each shower, we choose N_R =10 as benchmark for the following simulation studies.

3 Performance of Stereo Crystal ECal in Simulation

3.1 Setup of Stereo Crystal ECal Geometry

Simulations were conducted using BGO crystals in the CEPCSW [4] framework with Geant 4 [5, 6, 7], assuming ideal geometry without gaps or wrappers, no digitization, and a minimal energy threshold of 2 MeV for each crystal. The focus was on energy, position resolution, and particle separation, using a 10-layer segmentation as the baseline. The parameters used for SCECal configuration are listed in **Table 1**.

Table 1: Setup of Stereo Crystal ECal Barrel for simulation

Parameters	**Value**
Inner radius	1900 mm
Outer radius	2200 mm
Length along Z	6700 mm
Material	BGO crystal
Radiation length (R)	26.7 X0
Pointing angle	20 degrees
Sampling along R	10
Size of Crystals	[8.8-8.9]×10×316 mm^3

3.2 Simplified reconstruction method

The reconstruction method involves the following steps:

1) Identification of 2D Clusters:

Clusters are identified in two dimensions along Z-axis and azimuth angle, by finding the local maximum of the energy deposition and adding neighboring crystal with significant energy deposition. The crystal distance between even and odd layers along Z-axis are re-defined by considering the opposite pointing angle. The total energy is the sum of the energies of the crystals within the cluster.

2) Cluster splitting and merge

If multiple local maxima are found inside a cluster, it will be split into 2 if a significant secondary maximum is found and distance is larger than several crystals.

3) Hit Definition:

Hits are defined as the intersection points of two nearby clustered crystals along Z-axis, with known 3D positions. These hits give a 3D estimation of the energy deposition from stereoscopic crystals. The energy of a hit is firstly assigned as the sum of energy deposited in the 2 intersected crystal and then reevaluated by normalizing the hit energies in one cluster to the total energy calculated by the 2D clustering algorithm.

4) 3D position calculations

The direction and center position of the shower is then defined as the sum of the energy-weighted hit positions.

3.3 Resolution with simplified reconstruction

Using a Geant 4 particle gun to fire photons toward SCECal and checking the reconstructed properties w.r.t. true information, the Stereo Crystal ECal achieved energy and position resolutions as shown in **Figure 2**.

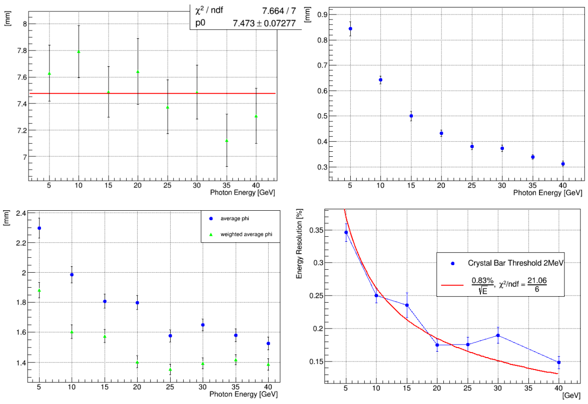

Figure 2: Position resolution for 5 GeV photons and energy resolution of Stereo Crystal ECal: Top-left: resolution on R of shower center; Top-right: resolution on Z-axis; Bottom-left: resolution on azimuth angle direction for non-weighted (Blue) and weighted (green) averages; Bottom-right: Relative energy resolution as function of incident photon energy.

3.4 Photons and pions separation

To evaluate the separation capabilities of the SCECal, two sets of simulations were conducted. The first set involved two 5 GeV photons, and the second set involved a 5 GeV photon and a 10 GeV pion.

Simulation Setup:

Photon-Photon Separation: two 5 GeV photons were simulated with varying distances between them along the azimuthal angle.

Photon-Pion Separation: a 5 GeV photon and a 10 GeV charged pion were simulated with varying distances between them along the azimuthal angle direction.

The distance here defined as the distance between these 2 particles at their incident point at inner radius of SCECal.

Success Criteria for Reconstruction:

For both scenarios, successful reconstruction is defined as identifying the particles with energy in the range of 3.3 GeV to 6.6 GeV for each photon.

The success of reconstruction efficiency as function of the distance is shown in **Figure 3**. Reasonable separation power is achieved with this simplified reconstruction: ~100% efficiency when > 60 mm for 2-photon separation and >90% efficiency when > 150 mm for photon-charged pion case.

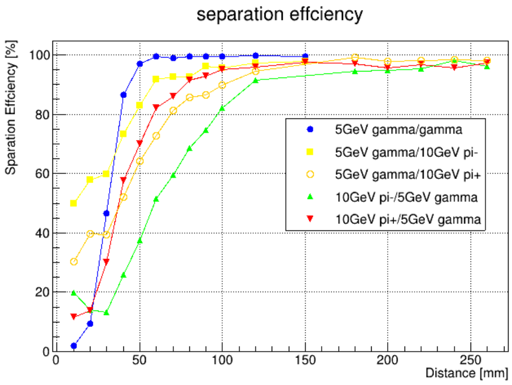

Figure 3: Separation efficiency as a function of distance between 2 particles incident point at SCECal. Due to the combination of different bending direction of charged pions in the magnet field of the inner part of the detector, and the different pointing angle of crystals, there are 4 cases for photon-charged-pion separation.

3.5 Particle Separation using Machine Learning

In this study, an end-to-end method [8] is employed for particle separation using machine learning techniques. The method involves the following steps:

1) Input Data:

The initial data consists of energy deposits in the crystal in a region near the shower cluster, represented in a two-dimensional (Z-axis, and azimuth angle) energy map.

2) Cluster Identification:

The energy map is processed to identify a number of clusters, which correspond to the number of incoming particles. If the identified number of clusters exceeds 1, then machine learning regression is used to reconstruct the energy of each particle.

3) Convolutional Neural Network (CNN) Regression:

A convolutional neural network is employed to perform regression analysis on the summarized energy data, using Keras [9]. The CNN is trained to predict the energy of each cluster. The training dataset consists of two photons with energies in the range of 0-10 GeV and varying distances between them.

4) Energy of Cluster:

The final output is the predicted energy of each cluster, which corresponds to the energy of the detected particles. The energy requirement of in the range of 3.3 GeV to 6.6 GeV for each photon is used only for diphoton separation study, not for the photon-pion study.

This machine learning-based method provides alternative approach for particle separation, leveraging the power of CNNs for energy prediction. The results demonstrate the huge improvement of this end-to-end method in the performance of 2-particle separation for the SCECal: 100% efficiency when > 20 mm for 2-photon separation as shown in **Figure 4**, and close to 100% efficiency when > 100 mm for photon-charged pion case as shown in **Figure 5**.

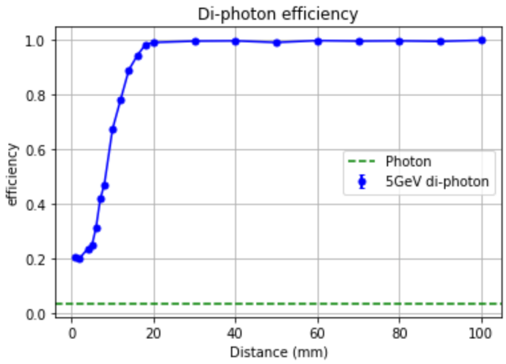

Figure 4: Separation efficiency as a function of distance between 2 photons incident point at SCECal. Green dashed line indicates the fake rate of one photon reconstructed as 2 photons.

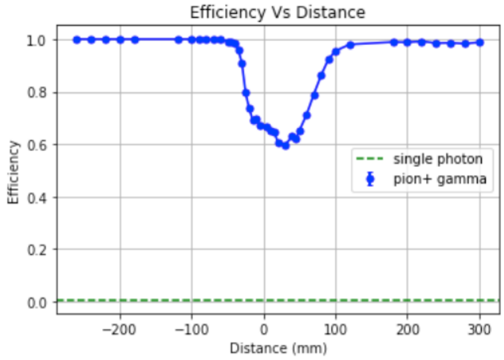

Figure 5: Separation efficiency as a function of distance between one photon and one charged pion incident point at SCECal. The negative distance represents photon approaching a pion shower at different side, as charged pion has bending, so does its shower developing. The worst separation is not centered at 0. The green dashed line indicates the fake rate of one photon reconstructed as one photon with one charged pion. The separation is non-zero even when the photon and the pion are in the same direction due to the separation on the detector radius of SCECal.

4 Summary

We present a novel configuration for a Homogenous Crystal Electromagnetic Calorimeter (ECal) featuring long crystal bars with two-dimensional readout at the outer end. Utilizing a stereo structure, this design provides measurements in the third dimension with a single free parameter (for a given inner, outer radius and fixed crystal lateral sizes), simplifying optimization. It has only one single crystal variant for the whole barrel region, ensures its uniformity in the azimuthal, longitudinal, and radial directions, and minimizes dead regions and ghost hits.

Preliminary simulations demonstrate the working principle, showing good energy resolution for EM objects. Machine learning techniques achieve excellent separation between two photons and photon-pion, with 100% efficiency at 20 mm and 100 mm respectively. These results demonstrated the working principles of SCECal. Further optimizations of the crystal and readout system are planned.

References

1. The CEPC Study Group, CEPC conceptual design report: Volume 2-physics & detector, arXiv:1811.10545
2. J. Marshall and M. Thomson, The pandora particle flow algorithm, arXiv:1308.4537187
3. CMS collaboration, The CMS electromagnetic calorimeter project: Technical Design Report, CMS, CERN, Geneva (1997).
4. CEPC working group, https://github.com/cepc/CEPCSW
5. S. Agostinelli et al.,Geant4 - A Simulation Toolkit, Nucl. Instrum. Meth. A 506 (2003) 250-303
6. J. Allison et al., Geant4 Developments and Applications, IEEE Trans. Nucl. Sci. 53 (2006) 270-278
7. J. Allison et al., Recent Developments in Geant4, Nucl. Instrum. Meth. A 835 (2016) 186-225
8. CMS Collaboration, Reconstruction of decays to merged photons using end-to-end deep learning with domain continuation in the CMS detector, Phys. Rev. D 108, 052002
9. Chollet, François and others, Keras, https://keras.io