

## Development of the CEPC analog hadron calorimeter prototype preprint

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### Abstract

The Circular Electron Positron Collider (CEPC) is a next-generation electron–positron collider proposed for the precise measurement of the properties of the Higgs boson. To emphasize boson separation and jet reconstruction, the baseline design of the CEPC detector was guided by the particle flow algorithm (PFA) concept. As one of the calorimeter options, the analogue hadron calorimeter (AHCAL) was proposed. The CEPC AHCAL comprises a 40-layer sandwich structure using steel plates as absorbers and scintillator tiles coupled with silicon photomultipliers (SiPM) as sensitive units. To validate the feasibility of the AHCAL option, a series of studies were conducted to develop a prototype. This AHCAL prototype underwent an electronic test and a cosmic ray test to assess its performance and ensure it was ready for three beam tests performed in 2022 and 2023. The test beam data is currently under analysis, and the results are expected to deepen our understanding of hadron showers, validate the concept of Particle Flow Algorithm (PFA), and ultimately refine the design of the CEPC detector.

### Full Text

#### Preamble

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Development of the CEPC analog hadron calorimeter prototype\* Yukun Shi,<sup>1, 2</sup> Anshun Zhou,<sup>1, 2</sup> Hao Liu,<sup>1, 2</sup> Jiechen Jiang,<sup>3</sup> Yanyun Duan,<sup>4, 5</sup> Yunlong Zhang,<sup>1, 2, †</sup> Zhongtao Shen,<sup>1, 2</sup> Jianbei Liu,<sup>1, 2</sup> Boxiang Yu,<sup>6, 3, 7</sup> Shu Li,<sup>8, 5</sup> Haijun Yang,<sup>9, 5</sup> Yong Liu,<sup>6, 3</sup> Liang Li,<sup>3, 10</sup> Zhen Wang,<sup>4, 5</sup> Siyuan Song,<sup>9, 5</sup> Dejing Du,<sup>3</sup> Jiaxuan Wang,<sup>1, 2</sup> Junsong Zhang,<sup>3</sup> and Quan Ji<sup>3</sup>

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State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026, China University of Science and Technology of China, Department of Modern Physics, Hefei 230026, China Institute of High Energy Physics, Chinese Academy of Sciences (CAS), 100049, Beijing, China Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, 201210, China Key Laboratory for Particle Physics, Astrophysics and Cosmology (Ministry of Education), Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai 200240, China State Key Laboratory of Particle Detection and Electronics, Institute of High Energy Physics, 100049, Beijing, China School of Physical Science, University of Chinese Academy of Sciences, 100049, Beijing, China Tsung-Dao Lee Institute & School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 201210, China School of Physics and Astronomy & Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China Department of Nuclear Technology and Application, China Institute of Atomic Energy, 102413, Beijing, China The Circular Electron Positron Collider (CEPC) is a next-generation electron-positron collider proposed for the precise measurement of the properties of the Higgs boson. To emphasize boson separation and jet reconstruction, the baseline design of the CEPC detector was guided by the particle flow algorithm (PFA) concept. As one of the calorimeter options, the analogue hadron calorimeter (AHCAL) was proposed. The CEPC AHCAL comprises a 40-layer sandwich structure using steel plates as absorbers and scintillator tiles coupled with silicon photomultipliers (SiPM) as sensitive units. To validate the feasibility of the AHCAL option, a series of studies were conducted to develop a prototype. This AHCAL prototype underwent an electronic test and a cosmic ray test to assess its performance and ensure it was ready for three beam tests performed in 2022 and 2023. The test beam data is currently under analysis, and the results are expected to deepen our understanding of hadron showers, validate the concept of Particle Flow Algorithm (PFA), and ultimately refine the design of the CEPC detector.

## Keywords

Hadronic Calorimeter, Scintillator Calorimeter, SiPM, particle flow algorithm, CEPC

The CEPC physics potential has been continuously explored by the CEPC Physics study groups, focusing on a wide range of topics, including Higgs precision measurements, precise EW measurements, Flavor Physics, and so on. Many Higgs boson couplings can be measured with precision about one order of magnitude better than those achievable at the High Luminosity LHC (HL-LHC)[11-15]. In addition, the CEPC is expected to improve the current precision of many of the electroweak observables by about one order of magnitude or more[8, 16].

These CEPC physics studies also identified a handful of critical detector requirements. A boson mass resolution(BMR) of 4% is required to separate the Higgs

bosons from the W and Z bosons in their hadronic decays, corresponding to an unprecedented jet energy resolution of 3-4% at 100 GeV[15]. To achieve this jet energy resolution, the baseline detector concept was guided by the particle flow algorithm (PFA) of measuring final state particles in the most suited detector subsystem[17, 18]. It employs an ultra-high granular calorimetry system to efficiently separate the final state particle showers, a low material tracking system to minimize the interaction of the final state particles in the tracking material, and a large volume 3 Tesla solenoid that encloses

## INTRODUCTION

The discovery of the Higgs boson marked a significant milestone in the field of particle physics [1, 2]. Now, the focus is on precisely measuring the properties of the Higgs boson[3-6], which has led to the proposal of the Circular Electron-Positron Collider (CEPC) as a future Higgs factory[7, 8]. The CEPC could operate at a center-of-mass energy  $\sqrt{s} = 240$  GeV with a luminosity of  $8.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , resulting in an integrated luminosity of  $21.6 \text{ ab}^{-1}$  for two interaction points over a decade, producing 4 million Higgs bosons[9, 10]. In addition, it will also be operated on the Z pole as a Z factory, perform a precise WW threshold scan, and be upgraded to a center-of-mass energy of 360 GeV, close to the tt threshold.

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Nucl. Sci. Tech. , ( ) 12960 scintillator tiles. These Scintillator tiles are read out by the silicon photomultiplier (SiPM) and SPIROC2E chips.

The scintillator tiles and electronics are housed in steel cassettes forming sensitive layers, which are then secured by the supporting framework along with the absorber plates.

the entire calorimetry system as illustrated in Fig. 1 [Figure 1: see original paper][8].

the barrel from inner to outer, the detector is composed of a silicon pixel vertex detector, a silicon inner tracker, a TPC, a silicon wrapper, an Electromagnetic Calorimeter(ECAL), a Hadronic Calorimeter(HCAL), a solenoid of 3 Tesla and a return yoke with embedded a muon detector.[8]. steel cassette, creating a sensitive layer for the AHCAL.

The calorimetry system plays a crucial role in the PFA for separating different particles in a jet and measuring the photons and neutral hadrons. The analog hadron calorimeter(AHCAL) with ultra-high granularity was proposed as one of

the options for the CEPC calorimetry. The AHCAL utilizing the SiPM-on-tile technology was previously developed by the CALICE group for the future linear collider, and a prototype was exposed to test beams in 2018[19–21]. However, considering that the CEPC will operate at a relatively low center-of-mass energy to prioritize precise Higgs measurements, it is essential to optimize the design of the AHCAL and build a prototype to validate its performance.

This article describes the design, construction, and tests of the CEPC AHCAL prototype that consists of a 40 layer steelscintillator sandwich structure. The design of the AHCAL prototype including the sensitive units, the readout electronics and the mechanical structure are introduced in Section 2.

Section 3 discusses the construction of the AHCAL prototype, covering the production and testing of scintillator tiles, SiPM testing, sensitive layer production, and prototype integration. In Section 4, the electronic test and the cosmic ray test are presented, demonstrating the functionality of the prototype. Finally, Section 5 provides a summary.

#### Sensitive unit

The scintillator is often used as the sensitive material for sampling calorimetry, along with the novel photosensitive device SiPM[24–32]. The AHCAL sensitive unit is composed of a scintillator tile and a SiPM. The  $40 \times 40 \times 3$  mm<sup>3</sup> scintillator tile is designed with a  $5.5 \times 5.5 \times 1.1$  mm<sup>3</sup> groove at the bottom to accommodate the SiPM[33], as depicted in adjacent to the SiPM for calibration[25].

The scintillator tiles were produced using a cost-effective injection molding technique, with the recipes and procedures undergoing eight iterations to achieve optimal performance[25]. Subsequently, the scintillator tile was wrapped with ESR, as shown in Fig. 3 Figure 3: see original paper.

The scintillator tile was tested by a Sr-90 source and a S14160-1315P SiPM[34, 35]. The result was shown in tile was approximately 17 p.e. (photon-electron). The nonuniformity of the scintillator tile was obtained by varying the position of the Sr-90 source. It turned out to be approximately 6.7%[33].

A simulation based on GEANT4 was carried out to investigate the impact of the SiPM on the performance of the AHCAL. A standalone AHCAL prototype geometry was built, and its responses to hadrons of different energies were simulated.

Various thresholds in the unit of MIP (Minimum Ionizing Particle) were applied in the simulation. The energy resolution improves while lower threshold is utilized, indicating that the SiPM with low crosstalk or high light yield should be selected for the prototype.

The energy deposition in a single AHCAL scintillator tile for 100 GeV hadrons was also simulated[36]. The majority of scintillator tiles exhibit energy depositions below 400 MIP, indicating that the dynamic range of the SiPM, estimated

as

## DESIGN OF THE AHCAL PROTOTYPE

The design of the CEPC AHCAL was optimized based on the PFA reconstruction results of the  $H \rightarrow gg$  channel within the CEPC software environment[22]. The optimized AHCAL design could achieve a Higgs boson mass resolution of 3.7%[23]. Following the optimized AHCAL design, the AHCAL prototype was expected to exhibit an energy linearity of approximately 1.5% and an energy resolution of approximately  $\sqrt{60\%}$  for pion particles with an energy ranging  $E(\text{GeV})$

from 10 GeV to 80 GeV. The prototype consists of 40 sampling layers, with each layer composed of 20 mm steel as the absorber and  $40 \times 40 \times 3$  mm<sup>3</sup> plastic scintillator tiles as the sensitive material, as illustrated in Fig. 2 [Figure 2: see original paper]. The total material of the prototype amounts to approximately  $5 \lambda$ . The sensitive area of the prototype is  $720 \times 720$  mm<sup>2</sup>, corresponding to

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HPK S14160-1315PS NDL EQR15-22-1313D-S Sensitive area(mm<sup>2</sup>)  $1.3 \times 1.3$   
 $4 \times 1.3 \times 1.3$  Number of pixels  $7396 \times 4$  Break down voltage(V) Dark count  
 rate(kHz) Photon detection efficiency(PDE)(%) Gain(10<sup>5</sup>) Cross talk(%) light  
 yield(p.e.) 40(2 pads)

The readout electronic system is responsible for collecting data from 12,960 channels across the 40 sensitive layers. It is composed of the front-end electronics and the DAQ system.

The front-end electronics consists of 120 HBU boards and the DAQ system consists of 40 Data InterFace(DIF) boards and a DAQ board, as shown in Fig. 4 Figure 4: see original paper. The HBU board is responsible for carrying the sensitive units and converting the analog signals of the sensitive units into digital signals, the DIF board is designed to collect the digital signals across the sensitive layer, and the DAQ board is intended to gather the data from the DIF boards and transmit it to the server.

On one side of the HBU, 108 SiPMs were soldered with LEDs positioned beside them, and the scintillator tiles were subsequently affixed using glue, as depicted in Fig. 4(b). On the opposite side of the HBU, three SPIROC2E chips were employed for the data collection of these 108 sensitive units, as illustrated in Fig. 4(c).

SPIROC is an auto-triggered, bi-gain, 36-channel ASIC which allows to measure on each channel the charge from one photoelectron to 2000 and the time with a 100 ps accurate TDC[40-42]. An analog memory array with a depth of 16 for each is used to store the time information and the charge measurement. A 12-bit Wilkinson ADC has been embedded to digitize the analog memory contents (time and charge on 2 gains). The data are then stored in a 4 kbytes RAM.

A very complex digital part has been integrated to manage all these features and to transfer the data to the DAQ. Each SPIROC chip contains 36 channels, corresponding to 36 sensitive units. Each SPIROC channel employs two preamplifiers with different gains to enhance the dynamic range, as depicted in Fig. 5 Figure 5: see original paper. Following the high gain preamplifier, a fast shaper and a discriminator are used to provide selftrigger. Once triggered, the signals from the high gain preamplifier and the low gain preamplifier are recorded in the analog memory after the slow shaping. Subsequently, the signals stored in the analog memory are converted into digital signals by a 12-bit ADC. It is important to note that the signal that triggers the SPIROC chip may not be exactly the same as the signal recorded. For instance, if a signal with an extremely narrow time width triggers the discriminator after the fast shaper, a pedestal may be recorded after the slow shaper.

A single sensitive layer of AHCAL contains 3 HBUs, corresponding to 324 sensitive units. A DIF board was de-

Number of events

Readout electronics system

Output(ADC)

a groove at the bottom to accommodate the SiPM and LED. (b) A scintillator tile wrapped with the ESR film. (c) The scintillator light response to Sr-90, from which the light yield of the scintillator was analyzed.

the pixel number divided by the light yield, should exceed To address the requirements of the CEPC AHCAL, several sensitive units of different SiPMs were evaluated[36, 37]. As a result, two types of SiPMs were selected for the AHCAL prototype, with their parameters listed in table 1 . Note that the EQR-22-1313D-S model has four pads, but only two of them were read out. the S14160-1315P SiPM was implemented on 38 AHCAL sensitive layers due to its low crosstalk and high dynamic-range. The EQR-22-1313D-S SiPM was utilized on the last 2 layers of the AHCAL prototype due to its high light yield and low price[38, 39].

DATASHEET

Spiroc Analog Part

The analogue core is composed of 36 channels embedding an input DAC for SiPM high voltage adjustment on 5V to tune gain channel by channel. Two preamplifiers allow the requested dynamic range and are followed by a trigger line made of a fast shaper and a discriminator. The charge measurement line is made of two variable slow shapers and two 16-depth SCAs. The block scheme of a channel is shown on the next figure.

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1.5pF  
0.1pF-1.5pF  
Low gain Preamplifier 0.1pF-1.5pF  
Slow Shaper  
Analog memory  
50 -100ns Depth 16  
8-bit DAC  
Depth 16  
Common to the 36 channels  
Conversion 80  $\mu$ s  
Variable delay  
Discri  
12-bit Wilkinson  
Fast Shaper  
Trigger  
Depth 16 DAC output  
Charge measurement  
50-100ns High gain Preamplifier  
selection  
Slow Shaper  
4-bit threshold adjustment  
10-bit DAC  
TDC ramp 300ns/5  $\mu$ s  
measurement  
Analog output

scheme of 9 SPIROC2E chips in a single AHCAL layer[43]. (c) Schematic view of the readout and data acquisition, involving 40 DIF boards and a DAQ board.

left), the HBU without scintillator(top right), the HBU assembled with scintillator(bottom left), the electronic side of the HBU and the DIF board(bottom right). (b) The sensitive unit on HBU. (c) The SPIROC2E chip on HBU.

allel readout scheme significantly enhanced the event readout rate to 3 kHz, comparing to the 83 Hz of serial readout scheme, enabling the prototype to

operate under the beamline environment[43]. The FPGA on the DIF board also processes commands from upstream, real-time control of the HBU board, and power supply to the HBU boards.

A DAQ system was designed to collect the data from 40 DIF boards and transmit the data to the server or the PC. Additionally, it synchronizes the clocks across the 40 AHCAL layers, and dispatches triggers and other commands to the DIF boards. Fig. 5(c) provides a schematic view illustrating the interactions between the front-end electronics and the DAQ system.

signed to collect signals from these HBUs with a parallel readout scheme, as illustrated in Fig. 5(b). 18 small FIFO (First In/First Out) modules and one large FIFO module were designed to cache the data from 9 SPIROC2E chips, enabling the simultaneous processing of the Analog to Digital (AD) conversion and the data transmission. This par-4

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The trigger system of the AHCAL consists of the SPIROC2E chips, the DAQ board and the trigger logic unit (TLU)[44]. The TLU distributes the trigger based on the coincidence measurement, which is determined by signals from other detectors or two specific layers of the AHCAL prototype. Once receives the trigger from the TLU, the DAQ sends a readout command to all SPIROC2E chips via DIF boards.

The SPIROC2E chips start the AD conversion and the FIFO cache starts to readout. If the absence of the trigger is over 4  $\mu$ s, the DAQ board sends an erase command to clear the cache.

Number of Events

Highgain output(ADC)

Calibration system

Highgain(ADC)

The non-uniformities among the numerous AHCAL channels would significantly impact the performance of the AHCAL. Therefore, a calibration system was developed. The SPIROC chips were modified to calibrate the pedestal and gain of each channel. SiPMs were coupled with LEDs for gain monitoring. Additionally, each sensitive layer was equipped with 48 temperature sensors to monitor temperature variations.

The pedestal of each channel could be obtained by a random trigger distributed from the DIF board to SPIROC chips.

The pedestal of this channel is determined as the mean value derived from the Gaussian fitting, as illustrated in Fig. 6 Figure 6: see original paper.

The DIF board could also inject electric charge into the SPIROC chip to probe the response of all channels. By varying the amount of injection charge, the gain ratio between high gain and low gain could be calibrated, as shown in response till it reaches its saturation point. With the linear part and the saturation part fitted separately, gain ratio could be obtained from the slope of the left line, and the saturation point is considered to be the intersection of two lines.

The LED placed adjacent to the SiPM is used to calibrate and monitor the SiPM. On a single HBU, 108 LEDs are divided into two groups to prevent light crosstalk. The SiPM response to the LED exhibits good single photon separation as illustrated in Fig. 6(c). The intervals between photon peaks are approximately 20 ADC, representing the gain of the SiPM.

The performances of SiPMs such as gain, PDE, and cross talk were notably influenced by temperature. Therefore, a temperature monitoring system consisting of 48 temperature sensors on each sensitive layer was implemented.

Number of Events

Lowgain(ADC)

Number of Events

Output(ADC)

fitted by a Gaussian. (b) Low and high gain calibration for a single AHCAL channel, fitted by 2 linear function. (c) LED spectrum of a single AHCAL channel, each peak corresponds to a photoelectron.

secures 40 absorber plates measuring 16 mm, with steel cassettes accommodating the scintillator tiles and electronics inserted into the gaps between these plates. The total thickness of the absorbing material is 800 mm, which includes contributions from the steel cassettes.

The design of the steel cassettes pursues the compactness of the AHCAL prototype, As illustrated in Fig. 7 Figure 7: see original paper. The top and bottom steel sheets of the cassettes, which serve as part of the absorbing material, are both 2 mm thick. This thickness ensures the stiffness of the cassette while maintaining portability. The scintillator tile, wrapped with ESR, has a thickness of 3.5 mm, while the PCB has a thickness of 2.5 mm. Additionally, a 4 mm space is designed for the electronic parts, providing a tolerance of 1 mm. The total thickness of the cassette is 14 mm.

Mechanical structure

The mechanical structure of the AHCAL prototype is composed of the steel cassettes and the supporting framework.

The steel cassette was designed to accommodate three HBUs and one DIF board. The supporting framework is responsible for securing the steel cassettes and absorber plates.

The design of the AHCAL prototype supporting framework is depicted in Fig. 7(a). This framework supports and

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Nucl. Sci. Tech. , () with 120 HBU boards that were manufactured and soldered with SiPMs. They were assembled into 40 sensitive layers with other components. Furthermore, 40 DIF boards, the DAQ board, 40 absorber plates, and the supporting framework were fabricated. After the integration of all these components, the AHCAL prototype was completed.

The scintillator tiles were produced efficiently with the injection molding technique and wrapped with ESR foils using a dedicated machine. A light yield test platform was developed to test this vast quantity of scintillator tiles[45]. The platform consists of a front-end board, a DIF board, a Sr-90 source loaded on a 3D servo motor, and a PC, as demonstrated in Fig. 8 Figure 8: see original paper. The front-end board followed the design of HBU, utilizing 144 S13360-1325PE SiPMs and 4 SPIROC2E chips, allowing for the testing of 144 scintillator tiles in a single run. tile. The peaks corresponding to photon electrons were identified, and the ADC value of a single photon-electron was estimated. The light yield of the scintillator tile was determined by the most probable value (MPV) obtained from fitting a convolution of the Landau and Gaussian functions. all the scintillator tiles. To improve the uniformity of the AHCAL prototype, only scintillator tiles with a light yield falling within a window of  $13 \pm 10\%$  p.e. were selected. Out of approximately 16000 scintillator tiles, 14219 were chosen under this criterion[46].

A SiPM test platform was developed based on customized jigs and LEDs. The customized jig can contain four SiPMs with a hole in the middle, allowing the LED light to pass through and activate the SiPMs. An FPGA was utilized to control the LED and readout signals from the SiPMs. Good photon electron separation was achieved on this platform, similar as what has been achieved with the LED calibration, as shown in Fig. 6(c). SiPMs produced in the same batch share similarities, such as the working voltage, while SiPMs from different batches differ in these characteristics. Therefore, in every batch, a few of SiPMs were tested with the SiPM test platform to ensure their quality.

of the AHCAL prototype.(c) The steel cassette assembled with three HBUs and the DIF board.

HBUs and the DIF board. The scintillator tiles are in direct touch with the bottom sheet, and six steel strips with a thickness of 3.5 mm are fixed to the bottom sheet secure the scintillator tiles and provide screw holes for HBU fixation. This design provides light shielding to the scintillator tiles while maintaining the compactness as much as possible. The HBUs will be attached to the top sheet with six small strips, leaving space for air cooling.

Production of sensitive units

Assembly of sensitive layers

The HBU boards were produced and soldered with SiPMs, SPIROC chips and other components. The scintillator tiles were assembled and secured onto the PCB using adhesive.

The HBUs along with scintillator tiles were secured in the steel cassette, as illustrated in Fig. 7(c). Prior to installing the top steel sheet, an electronic test was conducted to verify the basic functionality of this sensitive layer. The pedestals of all channels were checked. LED was activated group by group as to find out potential light crosstalk or dead channels.

## CONSTRUCTION OF THE AHCAL PROTOTYPE

In the construction process of the AHCAL prototype, a total of 16000 scintillator tiles were produced and tested, along

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## TESTS OF THE AHCAL PROTOTYPE

### Integration of the prototype

The supporting framework of the prototype was manufactured and then integrated with the steel absorbing plates, the gaps between the absorbers were tested to ensure the tolerance for sensitive layers. The sensitive layers were inserted layer by layer. Several fans were fixed on the right side of the prototype for air cooling, as depicted in Fig. 9 [Figure 9: see original paper]. The complete AHCAL prototype reaches a total weight of 5.5 tons.

In order to calibrate the pedestal and gain ratio of each AHCAL channel, an electronic test was conducted. Additionally, a cosmic ray test was performed to validate the functionality of the entire prototype.

### Electronic test

The electronic test was carried out using the calibration system introduced in Section II C. The pedestals of both high gain channels and low gain channels were obtained through an external trigger. Fig. 10 [Figure 10: see original paper] depicted the distributions of pedestals for all AHCAL high gain channels and low gain channels. Consistency within a chip and differences among chips were observed, indicating that non-uniformities among pedestals mainly originated from the variations among SPIROC chips.

The gain ratios and saturation points of all AHCAL channels were calibrated by the charge injection. The distributions of gain ratios and saturation points were depicted in Fig. 11 [Figure 11: see original paper]. sensitive layers have similar gain ratio, except for the last two layers due to the different junction capacitance of NDL SiPMs. Fig. 11(d) illustrates the differences in saturation points between SPIROC chips, indicating that the saturation points of AHCAL channels are primarily determined by the SPIROC chips.

spectrum of a single scintillator tile, each peak corresponds to a photoelectron[46]. (c) Light yield distribution of all 15524 scintillator tiles

#### Cosmic ray test

A cosmic ray test was performed on a dedicated test platform with 40 sensitive layers, as shown in Fig. 12 [Figure 12: see original paper]. During the cosmic ray test, signals from the top and bottom sensitive layers were directed to the TLU for coincidence measurement, with the DAQ board processing the data acquisition accordingly. The cosmic ray test spanned a month, during which half a million events were recorded. channels in a chip, showing noticeable dark noise. To suppress this dark noise, a threshold of 100 ADC was applied to each hit in the offline analysis, and track fitting was performed. The track fitting was conducted using hits that were

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Pedestal(ADC)

Gain Ratio

Channel ID

Number of Channels

Saturation Point(ADC)

Gain Ratio

Number of Channels

Layer

Chip ID

Saturation Point(ADC)

Number of Channels

Number of Channels

Number of Channels

(a)gain ratio. (b)saturation point. (c) Gain ratios of all sensitive layers. The last two layers exhibited different behavior because they utilize NDL SiPMs. (d)Saturation points varied from chip to chip within the sensitive layer.

Pedestal(ADC)

Channel ID

Pedestal(ADC)

Chip ID

structure to conduct the cosmic ray test. Absorbers were not involved.

low gain channels. (c) Pedestals from different chips in a sensitive layer, with obvious differences on pedestals between chips.

chip configurations. These variations in MPV resulted in differences in detection efficiency between sensitive layers, as shown in Fig. 14 [Figure 14: see original paper]. The majority of AHCAL sensitive layers demonstrated a detection efficiency of approximately 97%, with approximately 2% of undetected events attributed to dead areas between scintillator tiles. Layer 9 showed a lower efficiency due to improper configurations, which were subsequently rectified during the beam test.

the only hit in their respective layers. A minimum of 15 such hits was required in each event. poorly fitted events with high chi-square values were excluded, resulting in approximately 20,000 events displaying good tracking. In these events, noise hits were effectively eliminated by rejecting hits that were more than 120 mm away from the fitted track. noise hit rejection. The MIP peak was fitted using a convolution of Gaussian and Landau functions. After pedestal extraction, the MPV obtained from the fitting was 347 ADC, roughly corresponding to 17 photon electrons according to the LED calibration results.

It is important to note that the MPV varies from chip to chip due to the differences in SiPM voltages and SPIROC

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Layer

Number of Events

Number of Events

Layer

Highgain(ADC)

Layer

ray events.

Detection Efficiency

Pos Y(mm)

Pos X(mm)

Highgain(ADC)

direction. Cosmic ray spectra for a chip: (c) before track fitting and noise hit rejection, (d) after track fitting and noise hit rejection.

SUMMARY AND OUTLOOK

Several studies have been conducted on key components of the AHCAL prototype, including the sensitive units, the electronics, and the mechanical structure. These studies optimized the design of the AHCAL, thereby improving the performance of the AHCAL. A 40-layer AHCAL prototype with 12,960 channels was constructed. An electronic test and a cosmic ray test were conducted to the prototype. Pedestal and internal gain of each AHCAL prototype channel were calibrated with the electric test data. The results of the cosmic ray test indicated that the typical MIP response for the AHCAL chip was approximately 17 photoelectrons, while the detection efficiency for cosmic rays in the sensitive layers was approximately 97%. These results validated the proper functioning of the prototype and confirmed its readiness for the three beam tests conducted between 2022 and 2023.

The test beam data of the AHCAL prototype is currently under analysis. Preliminary results indicate that the AHCAL prototype demonstrates excellent imaging capability, enabling detailed visualization of the intricate inner structure of hadron showers. Additionally, its energy resolution reaches approximately  $\sqrt{60\%}$ , which satisfies the requirement  $E(\text{GeV})$

ments of the CEPC experiment. Further results will validate the feasibility of using the AHCAL as a hadron calorimeter for the CEPC experiment and will contribute to enhancements in the CEPC baseline detector design. Additionally, the test beam data presents an excellent opportunity to study hadronic shower shapes and refine the particle flow algorithm.

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