The development of a high granular crystal calorimeter prototype of VLAST

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Abstract

Very Large Area gamma-ray Space Telescope (VLAST) is the next-generation flagship space observatory for high-energy gamma-ray detection proposed by China. The observation energy range covers from MeV to TeV and beyond, with acceptance of 10 m^2sr. The calorimeter serves as a crucial subdetector of VLAST, responsible for high-precision energy measurement and electron/proton discrimination. This discrimination capability is essential for accurately identifying gamma-ray events amidst the background of charged particles. To accommodate such an extensive energy range, a high dynamic range readout scheme employing dual avalanche photodiodes (APDs) has been developed, achieving a remarkable dynamic range of 10^6. Furthermore, a high granularity prototype based on bismuth germanate (BGO) cubic scintillation crystals has been developed. This high granularity enables detailed imaging of the particle showers, improving both energy resolution and particle identification. The prototype' s performance is evaluated through cosmic ray testing, providing valuable data for optimizing the final calorimeter design for VLAST.

Full Text

Preamble

The development of a high granular crystal calorimeter prototype of VLAST∗ Yan-shuo Zhang,1, 2 Qian Chen,1, 2 Deng-yi Chen,3 Jian-guo Liu,1, 2 Yi-ming Hu,3 Yun-long Zhang,1, 2, † Yi-feng Wei,1, 2 Zhong-tao Shen,1, 2 Chang-qing Feng,1, 2 Jian-hua Guo,3, 4 Shu-bin Liu,1, 2, ‡ Guang-shun Huang,1, 2 Xiao-lian Wang,1, 2 and Zi-zong Xu1, 2 1State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026,

China 2Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China 3Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China 4School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, China Very Large Area gamma-ray Space Telescope (VLAST) is the next-generation flagship space observatory for high-energy gamma-ray detection proposed by China. The observation energy range covers from MeV to TeV and beyond, with acceptance of 10 m2sr. The calorimeter serves as a crucial subdetector of VLAST, responsi- ble for high-precision energy measurement and electron/proton discrimination. This discrimination capability is essential for accurately identifying gamma-ray events among the background of charged particles. To ac- commodate such an extensive energy range, a high dynamic range readout scheme employing dual avalanche photodiodes (APDs) has been developed, achieving a remarkable dynamic range of 106. Furthermore, a high granular prototype based on bismuth germanate (BGO) cubic scintillation crystals has been developed. This high granularity enables detailed imaging of the particle showers, improving both energy resolution and particle identification. The prototype' s performance is evaluated through cosmic ray testing, providing valuable data for optimizing the final calorimeter design for VLAST.

Keywords: High dynamic range, High granular calorimeter, BGO crystal, APD, VLAST

INTRODUCTION

Space-based gamma-ray astronomy offers unparalleled ad- vantages for observing the universe. Unburdened by Earth' s atmosphere, these observatories enjoy broad bandwidth cov- erage, enabling detection of gamma rays across a vast energy spectrum, from MeV to TeV. This wide coverage is crucial for studying diverse phenomena, from nuclear processes in stars to the extreme environments around black holes and pulsars.

The continuous monitoring capability of space-based tele- scopes provides excellent temporal resolution, allowing sci- entists to track the evolution of transient events like gamma- ray bursts and flares from active galactic nuclei. Moreover, the stable platform of space minimizes background noise, leading to high measurement precision and improved sensi- tivity for detecting faint sources. These combined advan- tages make space-based gamma-ray detection a crucial tool for investigating fundamental questions in astrophysics and cosmology, including the nature of dark matter, the origin of cosmic rays, and the mechanisms driving powerful astrophys- ical phenomena [1, 3–6].

Several successful gamma-ray missions have been success- fully carried out around the world. The Energetic Gamma- [7, 8] on the Comp- ray Experiment Telescope (EGRET) ∗ Supported by the Scientific Instrument Developing Project of the Chi- nese Academy of Sciences (No. GJJSTD20210009), the Scientific In- strument Developing Project of the Chinese Academy of Sciences (No.

PTYQ2024BJ0011), Special Support for Origins of Space Explorer (No.

GJ11050103) and the National Natural Science Foundation of China (Grant No. 12022503, 12025504, 12125505, 12227805, 12273120). † Corresponding author, ylzhang@ustc.edu.cn ‡ Corresponding author, liushb@ustc.edu.cn ton Gamma-ray Observatory (CGRO) significantly advanced our understanding of high-energy gamma-ray sources. The Astro-rivelatore Gamma a Immagini Leggero (AGILE) and the Fermi Large Area Telescope (Fermi-LAT) 12] have further expanded our knowledge, provided de- tailed maps of the gamma-ray sky and revealed a wealth [13–16]. The Dark Matter Particle Ex- of new sources (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) plorer (DAMPE) [17, 18] focuses on precise mea- [12–18] (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) surements of high-energy cosmic rays (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) [19–21] and gamma [6, 24], contributing to the search for dark matter signa- rays (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) tures.

Building upon these achievements, the Very Large Area gamma-ray Space Telescope (VLAST) [19–21] [25, 27, 29–31, 37] is proposed as the next-generation world- (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid leading space-based gamma-ray observatory with signifi- cantly enhanced capabilities. With a sensitive area of approx- imately 10 m2, an order of magnitude larger than Fermi-LAT, VLAST will achieve unprecedented sensitivity across a wider energy range, enabling the detection of fainter sources and more detailed studies of known objects. Its superior energy resolution and precise particle track reconstruction capabili- ties will further enhance its scientific reach, allowing for more accurate measurements of energy spectra and search for potential the dark matter signatures.

VLAST' s payload instrument comprises three key compo- nents working in concert, as shown in Fig. 1 [Figure 1: see original paper]. The outermost detector(cid:58) at the top, the Anti-Coincidence Detector (ACD) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) 22, 23(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) [29, 30], is constructed from plastic scintillators and serves as a veto system to discriminate against charged parti- cle background. The ACD also measures the energy loss of charged particles, aiding in the identification of light nuclei, while providing a trigger signal for inner detectors.

Beneath the ACD lies the Silicon Tracker and low Energy Fig. 1. Architecture of the payload of VLAST. gamma Detector (STED) 24, 25(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) [31, 32]. Configured as a 2 × 2 array, each quadrant of the STED contains eight super- layers. Each superlayer integrates a thallium-doped cesium iodide (CsI(Tl)) detector and two double-sided silicon mi- crostrip detectors. The CsI(Tl) detectors play a dual role: they directly measure the energy of MeV gamma rays and act as a converter for high-energy gamma rays, producing electron- positron pairs.

The innovative usage of CsI(Tl) as a converter, instead of denser materials like tungsten, improves the energy measurement of lower-energy gamma rays. The silicon mi- crostrip detector provides high angular resolution gamma-ray tracking and incident particle impact characterization through charged particle trajectory reconstruction.

At the base of the instrument is the High-Energy Imaging Calorimeter (HEIC), the heart of VLAST' s high-energy mea- surements, which employs bismuth germanate (BGO) crystal as its primary sensitive material. The HEIC can accurately measure the characteristic profiles of the energy deposition of the secondary particles induced from electromagnetic shower and hadronic shower for efficiently distinguishing electrons (or gamma-ray) from hadrons. The calorimeter is designed to cover an extensive energy range from 0.1 GeV to 20 TeV for gamma photons and electrons, together with performance specifications of energy resolution better than 2 % for 50 GeV photons, and the electron/proton separation capability should be better than 104, which is essential for separating gamma- ray signals from the background of cosmic-ray protons.

The HEIC serves as a critical component in VLAST detec- tors, primarily responsible for the precise energy measure- ments and particle identification, so its design is a critical aspect of VLAST' s development. Two potential design approaches are currently under consideration: (1) Following the DAMPE calorimeter design 26–29(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) [33–36], which utilizes orthogonally arranged elongated BGO crystal bars 30(cid:58)(cid:58)[37].

While the long bar design offers potential advantages includ- ing better energy resolution, the manufacturing of 1.2-meter- long, high-quality BGO crystals presents significant techni- cal challenges, and (2) Implementing a high-granular design composed of cubic BGO crystals, which offers a more practi- cal approach, and its finer granular scheme enables more ac- curate electromagnetic shower profile measurement of energy deposition. (cid:58)(cid:58)(cid:58)The(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) CaloCube(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)with (cid:58)(cid:58)(cid:58)the (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(ci consist(cid:58)(cid:58)of(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) project (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) performance.(cid:58) exhibit (cid:58)(cid:58)(cid:58)(cid:58)good(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) latter(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:5 configuration (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) similarity shares(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)mar 38–41, (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)which(cid:58)(cid:58)(cid:58)(cid:58)was(cid:58)(cid:58)(cid:58)th validated(cid:58)(cid:58)(cid:58)to crystals (cid:58)(cid:58)(cid:58)and(cid:58)(cid:58)(cid:58)(cid:58)has (cid:58)(cid:58)(cid:58)(cid:58)been(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) experiment (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) cubic (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) This article presents the development and testing process of the cubic blocks scheme HEIC prototype, including its design, construction, and experimental validation, which are crucial steps towards finalizing the design of VLAST. The de- sign of the prototype including the sensitive units, the readout electronics and the high dynamic range readout method are introduced in Section II. Section III details the construction of the HEIC-Cube prototype. In Section IV, the cosmic ray test is conducted, validating the functionality of the prototype.

Finally, Section V concludes with a summary of key findings and implications.

II. DESIGN AND DEVELOPMENT OF HEIC-CUBE PROTOTYPE High granularity is a crucial design feature for modern calorimeters used in collider experiments and astro particle physics. It refers to the fine segmentation of the calorime- ter into small, individually read-out sensitive elements. This fine segmentation allows for precise three-dimensional imag- ing of particle showers, enabling detailed reconstruction of the energy deposition pattern and improved particle identifi- cation. This is particularly important for distinguishing be- tween different types of particles, such as electrons, photons, and hadrons, and for reconstructing the complex topologies of high-energy particle interactions.

Several advanced calorimeter designs have been devel- oped by the CALICE collaboration, showcasing different ap- proaches to achieving high granularity. The silicon-tungsten (SiW) electromagnetic calorimeter utilizes silicon detectors interspersed with tungsten absorber plates 31(cid:58)(cid:58)(cid:58)[42]. Silicon detectors offer excellent spatial resolution, allowing for pre- cise measurements of the shower development. The tungsten absorber provides the necessary material for the electromag- netic shower development. The scintillator-tungsten/copper (ScW) ECAL employs plastic scintillators and a tungsten-copper alloy absorber [43, 44]. Scintillators offer fast response times and good light yield, while the tungsten- copper absorber provides a compact design. The analog hadron calorimeter (AHCAL) is based on plastic scintillators and iron absorbers [34-37] (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) [45-48]. Iron is a cost-effective absorber material for hadronic calorimetry. These sampling calorimeters, which alternate layers of active material (detec- tor) and passive material (absorber), provide good imaging capabilities but often compromise with energy resolution due to the sampling fluctuations inherent in their design. 32, 33(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) In contrast, homogeneous calorimeters, which are con- structed entirely of active material, offer the potential for both superior imaging and high-energy (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) energy resolu- tion. An example of this approach is the calorimeter design of the High Energy cosmic-Radiation Detection (HERD) exper- iment [38, 39] (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) [49-51], which utilizes an array of small-sized heavy crystals, such as LYSO, as sensitive units. The absence better (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) of passive absorber material in homogeneous calorimeters minimizes sampling fluctuations, leading to superior imag- ing performance and improved energy resolution. The HERD calorimeter, with its high granularity and homogeneous design, is optimized for measuring the energy and direction of high-energy cosmic rays. shifting (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) photodiodes (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) Intensified(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) The High Energy Imaging Calorimeter (HEIC) proto- type described previously adopts a similar approach to HERD, using BGO crystals as the active material. How- ever, a key difference lies in the readout scheme. While HERD employs fiber optic extraction (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)HERD(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:5 employs(cid:58)(cid:58)(cid:58)(cid:58)two systems(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)[52] to collect the scintillation light, independent (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) fibers(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)[53] (cid:58)(cid:58)to [40] :(cid:58)(cid:58)(cid:58)(cid:58)the(cid:58)(cid:58)(cid:58)(cid:58)first(cid:58)(cid:58)(cid:58)(cid:58)one (cid:58)(cid:58)(cid:58)(cid:58)uses (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:5 wavelength (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (IsCMOS) CMOS (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) deliver(cid:58)(cid:58)(cid:58)(cid:58)the (cid:58)(cid:58)(cid:58)(cid:58)light(cid:58)(cid:58)(cid:58)to (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) scientific(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) second (cid:58)(cid:58)(cid:58)one(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)makes(cid:58)(cid:58)(cid:58)us (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) whereas(cid:58)(cid:58)(cid:58)the(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) photo-diode cameras,(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) selected (APDs)(cid:58)(cid:58)(cid:58)are(cid:58)(cid:58 Avalanche(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) 54–56. 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The better(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) efficiency,(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)which (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) combination of high granularity, homogeneous crystal design, and fully embedded electronics makes the HEIC prototype a promising technology for future gamma-ray space observa- tion. board(cid:58)(cid:58)(cid:58)are(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) shares(cid:58)(cid:58)a(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) readout (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) experiment (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) contributes(cid:58)(cid:58)to(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) system(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) HERD (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) energy(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) reduced (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) improves(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) Our research group has (cid:58)(cid:58)(cid:58)We (cid:58)(cid:58)(cid:58)(cid:58)have developed a kind of high- granular BGO crystal calorimeter prototype designed for pre- cise energy measurements of up to 50 GeV, and it is expected to exhibit a fine energy resolution for electrons and gamma- rays. To match the profile of the electromagnetic shower more accurately, the scalability in longitudinal depth is more sig- nificant than in horizontal direction. Therefore, the prototype consists of 10 longitudinal layers, each layer arranged in a 5 × 5 array of cubic BGO crystal with size of 3 cm × 3 cm × 3 cm. The calorimeter exhibits a total depth of approximately 27 radiation lengths, which is supposed sufficient for con- taining high-energy electromagnetic showers. The photoelec- tronic devices are avalanche photodiodes (APDs) (cid:58)(cid:58)we(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) chose(cid:58)(cid:58)(cid:58)are (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)APDs, offering advantages in quantum efficiency and com- (PMT) tube (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) compared (cid:58)(cid:58)(cid:58)(cid:58)with(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) pactness (cid:58)(cid:58)(cid:58)(cid:58)when(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)[59]. The electronic boards for signal processing are embed- ded inside the calorimeter structure, minimizing signal path lengths and optimizing performance. This design aims for a balance between granularity, energy resolution, and com- pactness, making it suitable for various high-energy physics experiments. photomultiplier(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) A. Sensitive unit listed(cid:58)(cid:58)in(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) group(cid:58)(cid:58)of(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) properties (cid:58)(cid:58)is (cid:58)(cid:58)(cid:58)(cid:58) inherent(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) BGO crystals are widely applicable in high-energy physics experiments, including accelerator and space-based cosmic ray detection 41(cid:58)(cid:58)[60], due to several key properties. Their high density allows efficient interaction with high-energy par- ticles, while non-hygroscopicity ensures stable performance in varying environmental conditions. BGO' s high light yield translates to better energy resolution, crucial for precise mea- surements. (cid:58)(cid:58)A (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) table (cid:58)(cid:58)1.

Furthermore, the crystals are relatively easy to produce and process into desired shapes, simplifying detector construc- tion. The HEIC-Cube prototype employs a set of BGO scin- tillators with dimensions of 30 mm × 30 mm × 30 mm, and each surface of the crystal is encased in a 0.3 mm thick barium sulfate (BaSO4) reflective coating, as depicted in Fig. 2 Figure 2: see original paper.

This coating maximizes light collection by reflecting scintil- lation photons towards a designated 18 mm × 18 mm exit window on one surface of the cube, where a photodetector converts the light signal into an electrical pulse for subsequent analysis. This configuration optimizes light collection efficiency and relieves uneven light output to a certain extent, contributing to the detector’ s overall performance.

Table 1 . (cid:58)(cid:58)(cid:58)The (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)
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When coupling with the emission wavelength of BGO scintillator, semiconductor photodetectors will have a bet- ter performance with higher quantum efficiency compared to PMTs(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)[59]. The im- photomultiplier tubes (PMTs) proved efficiency translates to a stronger signal for a given amount of scintillation light. After comprehensive consid- eration of critical parameters including device dimension, gain characteristic, and linearity range, the HAMAMATSU S8664-0505 (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) 0505 avalanche photodiode (APD) [43] illustrated (cid:58)(cid:58)in(cid:58)(cid:58)(cid:58)(cid:58)Fig. (cid:58)(cid:58)(cid:58)(cid:58)2(b) (cid:58)was selected for this study. The [61] (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58) S8664-0505 features a 5 mm × 5 mm active area and em- ploys a P-on-N structure [44] (cid:58)(cid:58)(cid:58)[62], as shown in Fig. 2(c). The avalanche region P has an exceptionally thin profile of about 10 µm thick, which is crucial for minimizing unwanted sig- nals from secondary particles. In this configuration, only the electrons in the P region generated through photoelectric con- version or ionization process can initiate the avalanche multi- plication, amplifying the primary scintillation signal. In con- trast, holes produced in the N- and N+ regions simply drift into the avalanche region without producing an avalanche.

This unique structure effectively suppresses noise contribu- tions from secondary particles generated by clustering effect directly within the N- and N+ regions of the APD. This tar- geted avalanche mechanism enhances the signal-to-noise ra- tio, improving the accuracy of energy measurements.

Fig. 2. (a) 30 mm side length BGO cubic crystal, coated with white reflective film. (b) The HAMAMATSU S8664-0505 type APD. (c) Vertical structure diagram of the APD.

Considering the special environmental constraints of space-based experiments, the BGO crystal in our calorime- ter prototype is intentionally not directly coupled with the APDs to mitigate device damage caused by mechanical vi- brations. Instead, a 2 mm air (or vacuum) gap is maintained between the crystal surface and the APDs. This gap acts as a buffer, protecting the sensitive APDs from potential damage due to mechanical stresses and vibrations during launch and operation. The performance characteristics of this decoupled configuration was evaluated through measurements of its re- sponse to minimum ionizing particles (MIPs), as illustrated in Fig. 3 [Figure 3: see original paper]. The signal amplitude is about 23.8 fC, correspond- ing to a light yield of roughly 2900 photoelectrons per MIP (pe/MIP). The maximum value of equivalent electronic noise in the high-gain channels is approximately 0.6 fC. This low noise level, combined with the substantial MIP signal, results in a favorable signal-to-noise ratio, demonstrating the effec- tiveness of this design even with the introduced air gap. This approach ensures the longevity and stability of the detector system in the demanding conditions of space.

Module (PAM), and the Analog-to-Digital Module (ADM) 45, 46(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) [63, 64], and they are interconnected via a FPGA Mezzanine Card (FMC) connector. This system performs pre-amplification and digitization of APD signals, as demon- strated in Fig. 4 [Figure 4: see original paper]. Within the PAM, the JFETs are placed after each APD to suppress noise. A Pole-Zero Cancellation cir- cuit (PZC) then shapes the Charge Sensitive Amplifier (CSA) output, which is subsequently split into high-gain and low- gain channels to extend the dynamic range. This dual-gain approach allows for accurate measurement of both small sig- nals from minimum ionizing particles and larger signals from high-energy depositions.

The ADM houses a 12-bit, 32-channel Analog-to-Digital Converter (ADC) operating at 40 MSPS, digitizing the differ- ential signals from all gain channels, and then they are trans- mitted to the FPGA for storage in an internal buffer. Each individual waveform consists of 512 sampling points (corre- sponding to 12.8 µs), ensuring that both the baseline and the entire waveform are completely captured within the sampling window. The FPGA in ADM also serves as instruction pars- ing and clock distribution. Additionally, a temperature sensor is placed next to the central APDs to monitor its operational temperature for calibration and performance analysis. This circuit also includes a Digital-to-Analog Converter (DAC) calibration mechanism. The linearity of the high-gain and low-gain channels was obtained respectively from the DAC calibration, which will inject a group of step signals with varying amplitudes to the CSA unit. The results show (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) present that the response coefficients of the high and low gain chan- nels are 20.6 ADC/fC and 0.53 ADC/fC, with corresponding dynamic ranges are 150 fC and 7000 fC, respectively.

Fig. 4. Block diagram of electronic pre-amplifier module (PAM) and analog to digital module (ADM).

The digitized signals are transmitted to a data acquisition board through optical fiber. The Data Concentrator Module (DCM) [47] (cid:58)(cid:58)(cid:58)(cid:58) [65] primarily aggregates and buffers waveform data from multiple ADMs before uploading the consolidated data to the host computer via Ethernet for offline analysis and storage. Furthermore, the DCM incorporates essential functionalities including hit analysis, trigger generation, and command issuance. This hierarchical data acquisition sys- tem, from individual APDs to the central data collection, is designed for efficient and robust data handling in the laboratory environment. The inclusion of online data processing capabilities further optimizes data flow and reduces the vol- ume of data transmitted to the back-end host.

Fig. 3. A typical MIPs distribution from a detector unit.

B. Electronics The readout scheme adopts waveform sampling mode, capturing the complete signal shape from each APD. This sys- tem consists of two primary components: the Pre-Amplifier P +N +PNelectronholeHH11 L1 MIPsEntries 3973 / ndf 2c 71.18 / 65width 2.45-19.13 mpv 4.5-489.7 area 6.354e+02-2.582e+04 gsigma 6.5-101.2 0200400600800100012001400high-gain unfiltered channel MIPs [ADC]020406080100CountsHH11 L1 MIPsEntries 3973 / ndf 2c 71.18 / 65width 2.45-19.13 mpv 4.5-489.7 area 6.354e+02-2.582e+04 gsigma 6.5-101.2

1 C. High dynamic range readout The VLAST calorimeter is designed to detect primary cos- mic rays with energies exceeding 20 TeV. Simulation results indicate that for electrons/photons of primary energy of 20 TeV, the deposited energy approach (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) approaches(cid:58)7 TeV in a single crystal unit located in the shower center. The maxi- mum energy in one crystal corresponds to approximately 2.4 × 105 MIPs, where MIP represents the energy deposition by a minimum ionization particle through a BGO crystal of 30 mm thickness, which is approximately 27.4 MeV based on sim- ulations. To ensure accurate reconstruction of high-energy particle showers as well as reduce false triggering from elec- tronic noise, the energy lower threshold is set to 0.1 MIPs for each detection unit. This low

threshold is essential for captur- ing the full extent of the particle showers and distinguishing them from background noise. This condition necessitates the readout scheme of the calorimeter to achieve a dynamic range of 106.

If a single readout device is placed under a BGO crystal for fluorescence collection, its dynamic range is limited by ran- dom noise and saturation effect, so it cannot satisfy the design specification of the large area calorimeter. To overcome these limitations, many international studies have developed pho- todetectors or readout electronics with multiple gain stages by providing progressive sensitivity levels to extend the dynamic range. For example, the calorimeter of Fermi-LAT adopts a pair of photodiodes with distinct sensitive areas [10, 11] cou- pled to each end of individual scintillator. Furthermore, each of their readout electronics incorporate dual-gain channels to achieve additional dynamic range expansion. (cid:58), which ensures the effective energy range coverage from 20 MeV to about

300 GeV.

Following the adoption route of semiconductor photode- tectors, the HEIC employs a dual-APD configuration, where two APDs are positioned adjacent to each other in accordance with the scintillator geometry and coupled to the same fluo- rescence exit window of every BGO cubic units. These APDs are arranged directly facing the crystal' s light-emitting sur- face to ensure optimal fluorescence collection efficiency. A crucial element of the HEIC design is the incorporation of a light intensity attenuation filter. The entrance windows of one APD between the pair are covered with a fluorescence attenuation filter for extending the dynamic ranges for the high-energy end. This proportional attenuation allows the filter, (cid:58)(cid:58)an(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)
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amplifiers. The readout electronics used for both APDs are (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58
identical, and each APD leads out both an initial channel and an amplified channel on the back of the front-end board. This dual-APD configuration, combined with dual-gain channels in the readout electronics for each APD, provides the neces- sary dynamic range. de-

signed(cid:58)(cid:58)to(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) attenuating (cid:58)(cid:58)(cid:58)the(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) intensity(cid:58)(cid:58)(cid:58)of (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) remains(cid:58)(cid:58)(cid:58)it (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) attenuation (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) sheet(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)with (cid:58)a(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) amplitudes (cid:58)(cid:58)of(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) tune (cid:58)(cid:58)(cid:58)the(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) plastic(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) To validate this large dynamic range readout scheme, an LED-based illumination system was established, as shown depicted in Fig. 5 [Figure 5: see original paper]. The readout system was enclosed in a dark- (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) room environment to minimize stray light interference, with a LED positioned above the APD array. The LED served as a light source, simulating the scintillation light produced by the BGO crystal when interacting with cosmic rays. The pulse generator was used to excite LED, where the light in- tensity was precisely controlled through pulse voltage modu- lation [48] (cid:58)(cid:58)(cid:58)[66]. The pulse duration was set to 300 ns which is consistent with the fluorescence decay time of BGO crystal.

The signals from two APDs were independently processed by the readout electronics, with one APD covered by a filter with an attenuation coefficient about 1000 times placed on the in- cident window. Each APD signal is processed through two channels: a high-gain and a low-gain channel. This results in four readout channels per crystal: HH (High-gain from the unfiltered APD), HL (Low-gain from the unfiltered APD), LH (High-gain from the filtered APD), and LL (Low-gain from the filtered APD).

Fig. 5. Block diagram of the devices that utilizes a LED for measur- ing gain ratio.

During the testing process, the voltage of the pulse gen- erator was continuously adjusted to modulate the LED light intensity, which allows for a systematic investigation of the readout system' s response across a wide range of simulated energy depositions. The gain ratios between adjacent read- out channels were carefully measured and analyzed, as pre- sented in Fig. 6 [Figure 6: see original paper]. Linear fitting analysis revealed that the HH- HL and LH-LL ratios both exhibited values of approximately 36.5, which is determined by the design of the electron- amplitude (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) ics. (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) correlations respectively. (cid:58)The between (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(c HL-LH ratio was measured at about 31, a parameter intro- duced by the attenuation filter. illustrated (cid:58)(cid:58)in(cid:58)(cid:58)(cid:58)(cid:58)Fig.(cid:58)(cid:58)(cid:58)(cid:58)(cid:58

Based on these ratios and the MIPs response characteristics of the BGO sensitive unit from Fig. 3 (showing a signal am- plitude of 23.8 fC for a single MIP), the effective energy range of the four channel responses is detailed in Table

1(cid:58)2.

The combined dynamic range is evaluated as following: 4096−1200 5$×$10 × 36.36 × 31.39 × 36.76 = 2.4 × 106, where the numerator on the left represents the effective range of HH Figure (cid:58)(cid:58)(cid:58)(cid:58)6(a) (cid:58)(cid:58)(cid:58)and(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)6(c) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) high-gain(cid:58)(cid:58)(cid:58)(cid:58)and (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) channels(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) depict(cid:58)(cid:58)(cid:58)(cid:58)their(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) low-gain(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) ,(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) LEDWaveform generator0000000000000000000ADC$×1.1×40×1.1×$40LLLHHLHH

418 channel, and the denominator represents the amplitude of the minimum effective signal, which equals to 5 times of the standard deviation of electronic noise. It will exceed 2.3 (cid:58)(cid:58)(cid:58)will exceed (cid:58)(cid:58)(cid:58)2.4 × 106 according to the relative gains between the (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) readout channels, which proves to fulfill the design specifica- tions for large-area calorimeter applications, demonstrating the effectiveness of the dual-APD, dual-gain readout scheme.

Fig. 6. The linear fitting results between different channels. (a) from the uncovered APD: high-gain vs low-gain; (b) channels between 2 APDs: low-gain without filter vs high-gain with filter; (c) from the covered APD: high-gain vs low-gain.

Table 2 . The electronic and system dynamic range of different read- out channels Readout channel Electronic dynamic range System dynamic range

420 MIPs -294000 MIPs

3 fC -150 fC 10 fC -7 pC 3 fC -150 fC 10 fC -7 pC However, the LED-based illumination system has limita- tions. The light emitted by the LED is not uniform in all directions, and may not be evenly distributed across the APD array, leading to variations in the measured signals. This can affect the accuracy of the gain ratio measurements and the de- termination of the dynamic range. Therefore, further experi- mental validation using more uniform and representative ra- diation sources, such as radioactive sources or particle beams, is crucial for precise calibration and performance verification of the dual-APD, dual-gain readout system. This additional validation will provide a more accurate assessment of the sys- tem' s performance and its ability to accurately measure the energy of cosmic rays over the targeted energy range.

III. CONSTRUCTION OF THE HEIC-CUBE PROTOTYPE To validate the calorimeter performance in experimental conditions, a small-scale prototype was developed and tested in the laboratory. This prototype allows for a detailed inves- tigation of the calorimeter' s capabilities and serves as a cru- cial step towards the development of the full-scale instrument.

Fig. 7 [Figure 7: see original paper] illustrates a schematic diagram of its structure configu- ration. The prototype has 10 layers in vertical to ensure minimal leakage at the tail of the electromagnetic shower, allow- ing for a more accurate measurement of the total deposited energy. Each layer contains a 5 × 5 array of BGO crystals with the size of 3 cm × 3 cm × 3 cm, yielding a sensitive area of 15 cm × 15 cm per layer, sufficient to cover the lat- eral spread of a shower. A PAM board responsible for ampli- fying the signals from the APDs is embedded at the base of each sampling layer, and it is interconnected with an ADM board via a FMC connector. The ADM board performs the analog-to-digital conversion of the amplified signals. Each ADM employs 3 ADC chips, providing a total of 96 effective input channels for digitization. Given the matching number of channels in PAM and ADM, signals from the four vertex channels (LL0, LL4, LL20, and LL24) exhibiting the small- est amplitudes in each layer are excluded and remain uncon- nected to the back-end board. These channels corresponding to the corners of the crystal array are expected to contribute less significantly to the overall energy measurement.

Fig. 7. The schematic plot of the high granular cubic crystal calorimeter prototype. same(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) similar(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)
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ical design of the prototype is carefully considered to en- sure the precise positioning and stability of the BGO crys- tals and readout electronics. Fig. 8 Figure 8: see original paper shows the box of the sensitive layer made of carbon

fiber, a lightweight and strong material, which consists of a 5 × 5 array of arranged cells.

Each cell measures 31.6 mm × 31.6 mm to accommodate a BGO crystal placement with a small tolerance for position- ing and thermal expansion. The intercellular partitions have a uniform thickness of 1 mm, while the outermost frames exhibit a 2 mm thickness for additional structural reinforce- ment. Fig. 8(b) demonstrates the assembled configuration, where BGO crystals are precisely positioned within their re- spective cell and covered with attenuation filters above their optical windows. The filters are crucial for the dynamic range extension of the readout system, as they attenuate the light reaching one of the two APDs coupled to each crystal, which allows the system to measure a wider range of energies with- out saturation. The crystals are securely fixed in place using a black shock-absorbing adhesive (DOWSIL SE 9186 L Black Sealant). This adhesive provides both mechanical stability 020406080100120140160180200Low gain w/o filter [ADC]05001000150020002500300035004000High gain w/o filter [ADC]HL17_HH17_L4Entries 29534 / ndf 2c 9.565e+05 / 1202p0 0.03363-36.36 p1 2.005-613 - HL17_HH17_L4Entries 29534 / ndf 2c 9.565e+05 / 1202p0 0.03363-36.36 p1 2.005-613 - 050100150200250High gain w/ filter [ADC]05001000150020002500300035004000Low gain w/o filter [ADC]LH17_HL17_L4Entries 29456 / ndf 2c 2.004e+08 / 4756p0 0.1121-31.39 p1 6.809-94.48 - LH17_HL17_L4Entries 29456 / ndf 2c 2.004e+08 / 4756p0 0.1121-31.39 p1 6.809-94.48 - 020406080100120140160180200Low gain w/ filter [ADC]05001000150020002500300035004000High gain w/ filter [ADC]LL17_LH17_L4Entries 44804 / ndf 2c 9.99e+06 / 5710p0 0.01281-36.76 p1 0.7089-398 - LL17_LH17_L4Entries 44804 / ndf 2c 9.99e+06 / 5710p0 0.01281-36.76 p1 0.7089-398 - FPGAFPGAADCADCADCLEMOLEMOFPGAADCADCADCLEMOFPGAADCADCADCLEMOFPGAFPGAADCADCADCLEMOLEMOFPGAADCADCADCLEMOFPGAADCADCADCLEMOFPGAFPG connectionADM(96 channels)An ordinary APD and an APD covered by the filter30 mm BGO cubes5 rows × 5 columns × 10 layers DataFPGAPLLFanoutDCMSFP\$$\times 10 LEMO \times 10 DataFPGAPLLFanoutDCMSFP \times 10 LEMO \times 10 PMM \times 10 \times 10 PMM \times 10 \times 10 + 5.5 V \pm 6 VPMM \times 10 \times 10 + 5.5 V \pm$\$6VPAMPAM is short forPre-Amplifier ModuleADM is short forAnalog-to-Digital ModulePMM is short forPower Management ModuleDCM is short forData Concentrator ModuleServer

and optical isolation. Additionally, a carbon fiber honeycomb structure is placed above the filters to maintain the required air gap. coefficients(cid:58)(cid:58)in(cid:58)(cid:58)(cid:58)(cid:58)the (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) straightforward(cid:58)(cid:58)(cid:58)to (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) The prototype readout electronic board is shown (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) presented in Fig. 8(c), housing the readout for 25 crystals arranged in a horizontal layer. APDs have been soldered onto the PCB for efficient signal transfer and mechanical stability, and each crystal unit interfaces with 2 APDs. They share the same voltage supplied by a Nuclear Instrumentation Module (NIM) power source, and a compact high voltage low dropout regulator (LDO) will be installed at the top right-hand corner consistency

(cid:58)(cid:58)of (cid:58)(cid:58)(cid:58)the of PAM during subsequent assembly. (cid:58)(cid:58)(cid:58)The (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)
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(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) curely buckled onto the carbon fiber box according to locating bolts, while the corresponding ADM modules are connected and firmly fixed using screws, thereby constituting a complete sensitive layer as depicted in Fig. 8(e). The complete pro- totype configuration integrates 10 identical layers in vertical stacking and a corresponding back-end DCM . (cid:58)(cid:58)(cid:58)(cid:58) (Fig.
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In summary, the cubic (cid:58)(cid:58)(cid:58)high(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)
granular (cid:58)crystal calorimeter prototype comprises 10 detection layers, with each layer con- sisting of 25 BGO crystals with a side length of 30 mm. Each crystal is coupled with two APDs, generating 4 distinct am- plitude output signals. This design results in a system-wide configuration of 250 crystals and 960 active readout channels.

Accordingly, the detector' s electromagnetic shower contain- ment capability is characterized by 3.3 Molière radii in the transverse dimension and 26.8 radiation lengths in the lon- gitudinal dimension when particles hit the calorimeter along the central axis. These parameters ensure that the prototype is well-suited for precise electron energy measurement in the GeV range. The prototype provides valuable experimental data for validating the performance of the dual-APD, dual- gain readout scheme and for characterizing the calorimeter’ s response to electromagnetic showers, paving the way for the development of the full-scale VLAST calorimeter.

IV. PERFORMANCE OF THE PROTOTYPE SYSTEM To further validate the calorimeter prototype and assess its performance under real-world conditions, an experimental setup was established for ground-based cosmic ray measure- ments. This testing involves exposing the prototype to the natural flux of cosmic rays, which serve as a readily available source of high-energy particles, providing an opportunity to evaluate its response. Fig. 9 [Figure 9: see original paper] depicts (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) demonstrates the experi- mental setup for this cosmic ray test.

Fig. 8. (a) The carbon fiber framework. Each grid will house a BGO block. (b) The framework assembled with BGO cubes and plastic attenuators. (c) the end-product of PAM. It is interlocked with the peripheral carbon fiber framework of a BGO crystal layer. (d) the back-end DCM. (e) an entire overview of the calorimeter prototype component with a BGO crystal layer at the bottom.

Muons, being highly penetrating particles, are the dom- inant component of cosmic rays reaching the Earth’s sur- face. They readily traverse the calorimeter, depositing en- ergy primarily through ionization, typically interacting with the calorimeter as MIPs. This behavior makes them ideal for characterizing the performance consistency among the indi- The distribution of pedestal values provides insights into the electronic baseline and equivalent noise characteristics of each channel. Fig. 10 [Figure 10: see original paper] illustrates two examples of pedestal distributions for a high-gain channel 10(a) and a low-gain channel 10(b). The high-gain channel exhibits a mean value of approximately 1076 ADC counts with a standard deviation of 7 counts, while the low-gain channel has a mean value of about 174 ADC counts with a standard deviation of less than 1 count. These values reflect the different gain settings and noise levels of the two channel types.

Further analysis reveals significant variations in the mean pedestal values between different channels, as illustrated depicted (cid:58)in subsequent figures (10(c) and 10(d)) showing (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) the mean values derived from Gaussian fitting of high-gain and low-gain channels during a one-day test. These variations can be attributed to several factors, including non-uniformity of temperature across the BGO crystals and APDs at different spatial locations, disparities in gain coefficients among APDs despite the common bias high voltage, and potential slight light leakage effects. Temperature variations can affect the performance of both the BGO crystals and the APDs, leading to changes in their response. Variations in the gain coeffi- cients of the APDs can arise from manufacturing tolerances or differences in their operating conditions and recommended setup. Light leakage can introduce unwanted background sig- nals, affecting the pedestal values. These factors exert vari- ous degrees of influence on the signal generation and ampli- fication processes, thereby endowing each channel’ s pedestal with distinct characteristics.

Fig. 10. (a) An example of pedestal distribution in HH12 channel Layer 7. (b) An example of pedestal distribution in HL12 channel Layer 7. (c) and (d) 2 show (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) demonstrate(cid:58)statistical results of all the mean value of pedestals in high-gain channels and low-gain channels factor(cid:58)(cid:58)in(cid:58)(cid:58)(cid:58)the(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) from 1 day’s test. (cid:58)(cid:58)(cid:58)The(cid:58)(cid:58)(cid: channel conversion(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) channel(cid:58)(cid:58)is(cid:58)(cid:58)(cid:58)(cid:5 ADC/fC,(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)while(cid:58)(cid:58)(cid:58)the (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)is(cid:58)(cid:58)(cid:58)(cid:58)20.6(cid:58)(cid:58)(cid:58)(cid: ADC/fC, (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) factor (cid:58)(cid:58)in (cid:58)(cid:58)(cid:58)the (cid:58)(cid:58)(cid:58)low(cid:58)(cid:58)(cid:58)(cid:58)ga (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) according(cid:58)(cid:58)to(cid:58)(cid:58)(cid:58)(cid:58)[64].

To determine the gain coefficients between the high-gain and low-gain channels, a linear fitting analysis is performed.

The amplitudes relationship of the two output signals from the same APD without attenuation filter coverage , are analyzed Fig. 9. Overview photograph of the cubic calorimeter prototype when conducting cosmic ray test. vidual detector units within the calorimeter. By analyzing the signals generated by muons passing through the detector, it’ s possible to identify any variations in response between different channels and assess the overall uniformity of the calorimeter.

The data acquisition system employed in this experiment utilizes an over-threshold triggering mode, which means that data is recorded only when the signal in a readout channel ex- ceeds a predefined threshold. This threshold is set to 20 times the sigma value relative to its respective pedestal average for each channel. The pedestal represents the baseline signal level of each channel when no particle is interacting with the detector, while its width reflects the level of noise. Setting the (approximate (cid:58)(cid:58)(cid:58)130(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)ADC threshold at 20 times the sigma value (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cic equivalent(cid:58)(cid:58)to(cid:58)(cid:58)(cid:58)0.3(cid:58)(cid:58)(cid:58)(cid:58)MIP(cid:58)(cid:58)(cid:58 helps to discriminate real values, (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) signals from electronic noise fluctuations.

The experiment was conducted over a period of two months, accumulating a substantial amount of data. After excluding data associated with mistaken operations or other anomalies, a total of 59 valid data packages were obtained.

The daily binary recording files indicate an interaction rate of approximately one million events per day. This high event rate provides a statistically significant dataset for analysis.

Some preliminary analysis results are shown (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) presented here from the routine cosmic ray test. The offline data pro- cessing involves several steps to extract meaningful informa- tion from the raw data. First, the binary files are unpacked to retrieve the 512 sampling points datasets for each channel.

These sampling points represent the digitized signal wave- form over time. The average value of the first 128 sampling points is calculated and used as the pedestal value for that channel. The maximum code value among all 512 points is identified as the channel' s peak value, representing the maxi- mum amplitude of the signal. The effective amplitude of each channel is then determined by subtracting the pedestal value from the peak value. This procedure is applied consistently across all daily data packets to ensure uniformity in the anal- ysis.

HH channel: 20.6 ADC ∼ 1 fCEntries 891700 / ndf 2c 821.6 / 4Constant 3.038e+02–2.121e+05 Mean 0.0–1076 Sigma 0.008–6.625 10401050106010701080109011001110HH12 L7 pedestal [ADC]020406080100120140160180200220310 • CountsHH channel: 20.6 ADC ∼ 1 fCEntries 891700 / ndf 2c 821.6 / 4Constant 3.038e+02–2.121e+05 Mean 0.0–1076 Sigma 0.008–6.625 HL channel: 0.53 ADC ∼ 1 fCEntries 614900 / ndf 2c 4.509e+04 / 3Constant 6.449e+02–3.756e+05 Mean 0.0–174.5 Sigma 0.0007–0.6044 170171172173174175176177178HL12 L7 pedestal [ADC]050100150200250300350400310 • CountsHL channel: 0.53 ADC ∼ 1 fCEntries 614900 / ndf 2c 4.509e+04 / 3Constant 6.449e+02–3.756e+05 Mean 0.0–174.5 Sigma 0.0007–0.6044 HH_{{{LH}}*{{pedestal}}}*{meanEntries} 482Mean 1068Std Dev 162.46008001000120014001600H channels pedestal mean [ADC]05101520253035CountsHH_{{{LH}}*{{pedestal}}}*{meanEntries} 482Mean 1068Std Dev 162.4HL_{{{LL}}*{{pedestal}}}*{meanEntries} 415Mean 116.9Std Dev 35.21406080100120140160180200220L channels pedestal mean [ADC]024681012141618CountsHL_{{{LL}}*{{pedestal}}}*{meanEntries} 415Mean 116.9Std Dev 35.21

620 demonstrates (cid:58)(cid:58)(cid:58)the(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) 11(b)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) fitting,(cid:58)(cid:58)(cid:58)(cid:58)and (cid:58)(cid:58)(cid:58)(cid:58) before and after amplification by the front-end electronics, as (cid:58)(cid:58)is presented in Fig. 11 Figure 11: see original paper. The linear region of the rela- tionship between the two signals is fitted using a first-order polynomial function. The average slope value obtained from this fit (cid:58)(cid:58)(cid:58)Fig.(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) collects(cid:58)(cid:58)(cid:58)(cid:58)and (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(c
value slope (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) average (cid:58)is approximately 37.5, their(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) linear(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) after (cid:58)(cid:58)(cid:58)(cid:58)(cid:58) (cid:58)(cid:58)(cid:58)(cid:58) indicating that these gain coefficients are similar and main- tain reasonable consistency with the original design specifi- cations. Given that the energy deposition of muons in cosmic rays is generally relatively small, only the uncovered APDs with high-gain can produce detectable MIP signals. There- fore, it is challenging to calibrate the remaining two coefficients (HL-LH ratio and LH-LL ratio) using a single data file.

Fig. 11. (a) A typical relationship between the effective amplitudes in HL12

channel Layer 7 and HH12 channel Layer 7. (b) A statis- tical result of all the gain ratios of signals in high-gain channels and low-gain channels from 1 day' s test.

A group of specific selection criteria are defined to iden- tify MIP events within the dataset. A MIP event is defined as an event in which at least 7 out of the 10 detection layers output effective signals, with no more than 3 over-threshold channels per layer, and there should be at least 2 of the first 3 layers and 2 of the last 3 layers meet these criteria. This se- lection ensures that the identified events correspond to muons traversing the entire calorimeter. Fig. 12 [Figure 12: see original paper] depicts a represen- tative event that satisfies these requirements. The selected MIP events are then analyzed channel by channel. The signal distribution for each channel is fitted using a Landau convo- luted Gaussian function, which is commonly used to model the energy loss distribution of charged particles traversing a material. The Most Probable Value (MPV) obtained from the Landau distribution component represents its response to MIP in a given crystal. For example, the HH12L7 channel illus-
trated(cid:58)(cid:58)in(cid:58)(cid:58)(cid:58)(cid:58)Fig.(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)13(a)(cid:58)e
an MPV of approximately (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)

370 ADC counts after pedestal subtraction, corresponding to

an estimated input charge of about 18 fC for MIP signals.

Analysis of all the HH channels reveals that each channel has a characteristic MPV, as shown in Fig. 13 Figure 13: see original paper. These vari- ations in MPV can be attributed to several factors, similar to the variations observed in the pedestal values. These factors include temperature fluctuations, variations in bias voltage between devices, and environmental stray light interference.

The long-term stability of the calorimeter' s response was also investigated. The cosmic ray experiment has been run- ning for two months, allow- ing for the observation of long- term trends. Some parameters, such as the pedestal and MPV of Landau component, showed gradually emerging regular patterns over time. Fig. 14 [Figure 14: see original paper] demon- strates that the MPV of indi- incident Fig. 12. A typical event which are (cid:58)is selected as MIPs(cid:58)a(cid:58)(cid:58)(cid:58)(cid:58)MIP (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) event. (cid:58)(cid:58)(cid:58)(cid:58)
Fig. 13. (a) A typical MIPs distribution after subtracting its own pedestal in HH12 channel Layer 7. (b) A statistical result of all the most probable value of
MIPs in high-gain channels from 1 day's test.(cid:58)(cid:58)(cid:58)The(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(c
ADC/fC, channel (cid:58)is(cid:58)(cid:58)(cid:58)(cid:58)20.6 (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(ci
according(cid:58)(cid:58)to(cid:58)(cid:58)(cid:58)(cid:58)[64]. (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(c
factor(cid:58)(cid:58)in(cid:58)(cid:58)(cid:58)the (cid:58)(cid:58)(cid:58)high(cid:58)(cid:58)(cid:58)(cid:58)gai
(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) conversion (cid:58)(cid:58)(cid:58)(cid:58)
vidual channels varied within a relatively small range, while the pedestal values

remained remarkably stable throughout the testing period. The temperature of the channels, shown presented as dotted lines in Fig. 14(b) with reference to the (cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58)(cid:58) right axis, exhibits a significant correlation with the observed signal variations, further supporting the hypothesis that tem- perature fluctuations play a significant role in the observed channel-to-channel variations. This long-term stability is cru- cial for ensuring the reliable performance of the calorime- ter over extended periods of operation. Consequently, more stringent temperature control requirements have been put for- ward for the satellite' s payload platform.

V. CONCLUSION To investigate the physical characteristics of high-energy gamma-rays in cosmic environment and explore the funda- mental nature of dark matter particles, we propose the devel- opment of a Very Large Area gamma-ray Space Telescope (VLAST), which will serve as China' s next gen- eration flag- ship satellite platform for gamma-ray space-based astronom- ical observation. A key component of VLAST is a high- 020406080100120140HL12 L7 amplitude [ADC]05001000150020002500300035004000HH12 L7 amplitude [ADC]2060Entries 1323 / ndf 2c 2.82e+05 / 329slope 0.1411-37.65 intercept 4.297-13.05 - 2060Entries 1323 / ndf 2c 2.82e+05 / 329slope 0.1411-37.65 intercept 4.297-13.05 - HH_{{{HL}}*{{gain}}}*{ratioEntries} 248Mean 36.6Std Dev 0.7163334353637383940Gain ratio0510152025CountsHH_{{{HL}}*{{gain}}}*{ratioEntries} 248Mean 36.6Std Dev 0.716012345X direction012345Y direction012345678910Z direction00.511.522.5(energy deposition [MIPs]) + 1HH11 L1 MIPsEntries 4205 / ndf 2c 25.82 / 26width 1.96-24.59 mpv 1.5-371.7 area 7.205e+02-3.389e+04 gsigma 3.88-37.09 0100200300400500600700800900HH12 L7 MIPs [ADC]020406080100120140160180200220CountsHH11 L1 MIPsEntries 4205 / ndf 2c 25.82 / 26width 1.96-24.59 mpv 1.5-371.7 area 7.205e+02-3.389e+04 gsigma 3.88-37.09 HH_{{{MIPs}}*{{mpvEntries}}} 246Mean 487.1Std Dev 141.3200300400500600700800900HH MIP mpv [ADC]0246810121416CountsHH*{{{MIPs}}_{{mpvEntries}}} 246Mean 487.1Std Dev 141.3

10 totype utilizes an array of 30 mm cubic BGO crystals as scin- tillators, coupled with a custom-designed electronics system featuring dual-APD dual-gain readout scheme for each crys- tal. This two APDs configuration, combined with attenuation filters, enables a wide dynamic range, crucial for detecting both low-energy and high-energy gamma rays.

Initial test- ing of the prototype, including LED luminescence tests and ground-based cosmic ray measurements, has demonstrated promising results. The noise level of the dual-APD config- uration has been determined to be approximately 0.1 MIPs, while maintaining an exceptional dynamic range of 2 × 106 for the complete readout system. This wide dynamic range allows the calorimeter to detect signals ranging from the rea- sonable small to the much larger energy depositions of high- energy cosmic rays.

Future optimization efforts will focus on refining several key aspects of the calorimeter design and performance. (1) Precise channel-by-channel calibration of the effective sensi- tive regions will be implemented using a set of dedicated light intensity monitoring system. This calibration will ensure ac- curate energy measurements across the entire calorimeter. (2) An improved attenuator filter design will be applied to opti- mize the balance between a wide enough overlap region be- tween the high-gain and low-gain channels and a large dy- (3) Ongoing improvements in ther- namic range coverage. mal management and grounding configurations will further enhance the stability and performance of the readout elec- tronics. Finally, a prospective beam test is planned to comprehensively evaluate the calorimeter' s performance characteris- tics under controlled conditions with known particle beams.

This beam test will provide crucial data for validating the calorimeter' s design and optimizing its performance for the VLAST mission. [7] G. Kanbach, D. L. Bertsch, A. Favale, gamma-ray EGRET project telescope) GRO. Space Science Reviews, 49(1): https://doi.org/10.1007/BF00173744 Gamma-Ray (energetic NASA' s et al., The

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Note: Figure translations are in progress. See original paper for figures.

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