Design and initial performance of the CEE ZDC readout electronics

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Abstract

The CSR External-target Experiment (CEE) is the first large-scale nuclear physics experiment in China to operate independently in the GeV energy regime. As an essential detector in the CEE, the Zero-Degree Calorimeter (ZDC) is designed to measure the collision centrality and reaction plane in nucleus-nucleus collisions. To address Photomultiplier Tube (PMT) signal saturation induced by nuclear fragments, the ZDC adopts a readout architecture that combines fan-shaped Plastic Scintillators with Hamamatsu R7525/R3478 PMTs equipped with third- and sixth-dynode outputs, with a gain ratio of 100:1. A dedicated readout electronics system was developed, comprising 12 Front-End Cards (FECs), 12 Readout Control Units (RCUs), and submodules for triggering, Data Acquisition (DAQ), and clock synchronization. Following hardware-based digitization of the detector signals, the ZDC electronics employs a modular and pipelined algorithmic architecture within the logic, enabling efficient on-line conversion from raw waveforms to physical event frames. It supports flexible switching among multiple trigger and data acquisition modes, meeting the bandwidth-reduction requirements at high count rates while ensuring the accuracy and integrity of offline analysis, thereby providing reliable online data-processing capability and ensuring stable operation of the ZDC detector under various working conditions. Test results demonstrate that the system achieves an Integral Nonlinearity (INL) below 0.4% and a Root-Mean-Square (RMS) noise level below 1 mV, while maintaining stable performance under a magnetic field of 1200 Gs and over a temperature range of 0-45℃. A 20-day beam test verified that the baseline drift remains below 1 mV, that the charge peaks corresponding to nucleons and nuclear fragments with Z=1-6 are clearly distinguishable, and that the energy resolution is below 15%, thereby fully satisfying the requirements of the CEE. This work establishes a reusable technical framework for the

electronics design of high-energy detectors in large-scale scientific projects.

Full Text

Preamble

Design and initial performance of the CEE ZDC readout electronics∗ Xian-Qin Li,1, 2 Hai-Bo Yang,1, 2, † Liang-Tao Wen,3 Jiang-Peng Zhou,3 Yuan-Hang Liu,1, 4 Shi-Kai Wang,1, 4 Wei Zhang,1, 5 Hua Pei,3 Feng Liu,3 Ya-Ping Wang,3 Cheng-Xin Zhao,6 Yu-Hong Yu,1, 2 and Zhi-Yu Sun1, 2

State Key Laboratory of Heavy Ion Science and Technology, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China School of Physical Science and Technology, Central China Normal University, Wuhan 430079, China School of Physics and Electronic Engineering, Northwest Normal University, Lanzhou 730070, China School of Nuclear Science and Technology, Harbin Engineering University, Harbin 150001, China School of Integrated Circuits, Jiangnan University, Wuxi 214401, China The CSR External-target Experiment (CEE) is the first large-scale nuclear physics experiment in China to operate independently in the GeV energy regime. As an essential detector in the CEE, the Zero-Degree Calorimeter (ZDC) is designed to measure the collision centrality and reaction plane in nucleus-nucleus collisions. To address Photomultiplier Tube (PMT) signal saturation induced by nuclear fragments, the ZDC adopts a readout architecture that combines fan-shaped Plastic Scintillators with Hamamatsu R7525/R3478 PMTs equipped with third- and sixth-dynode outputs, with a gain ratio of 100:1. A dedicated readout electronics system was developed, comprising 12 Front-End Cards (FECs), 12 Readout Control Units (RCUs), and submodules for triggering, Data Acquisition (DAQ), and clock synchronization. Following hardware-based digitization of the detector signals, the ZDC electronics employs a modular and pipelined algorithmic architecture within the logic, enabling efficient on-line conversion from raw waveforms to physical event frames. It supports flexible switching among multiple trigger and data acquisition modes, meeting the bandwidth-reduction requirements at high count rates while ensuring the accuracy and integrity of offline analysis, thereby providing reliable online data-processing capability and ensuring stable operation of the ZDC detector under various working conditions.

Test results demonstrate that the system achieves an Integral Nonlinearity (INL) below 0.4% and a Root-MeanSquare (RMS) noise level below 1 mV, while maintaining stable performance under a magnetic field of 1200 Gs and over a temperature range of 0-45 ∘ C. A 20-day beam test verified that the baseline drift remains below 1 mV, that the charge peaks corresponding to nucleons and nuclear fragments with Z=1-6 are clearly distinguishable, and that the energy resolution is below 15%, thereby fully satisfying the requirements of the CEE. This work establishes a reusable technical framework for the electronics design of high-energy detectors in large-scale scientific projects.

Keywords

HIRFL-CSR;CEE; Readout electronics;ZDC

INTRODUCTION

the Compressed Baryonic Matter (CBM)[6] experiment, with a beam energy of 45 GeV/u. In this energy range, the collid21 ing nuclei become highly compressed, leading to both high 22 temperatures and extremely high baryon densities in the in23 teraction region. This regime is intended to explore the QCD 24 phase transition at high baryon density and to search for the 25 critical point.

Phase transitions at high temperatures may have taken place in the early universe, while high-density matter may 4 characterize the interior states of compact astrophysical ob5 jects.

The phase transition in Quantum Chromodynamics 6 (QCD)[1] between these two regimes can only be investigated 7 through relativistic heavy-ion collision experiments. Heavy8 ion collisions at different energies probe distinct regions of 9 the QCD phase diagram: the Relativistic Heavy Ion Collider 10 (RHIC)[2] in the United States operates at a center-of-mass 11 energy of 200 GeV per nucleon pair, while the Large Hadron 12 Collider (LHC)[3] at CERN can reach center-of-mass ener13 gies of up to 5.4 TeV. These collisions generate extremely 14 high temperatures, and their primary scientific objective is 15 to search for the Quark-Gluon Plasma (QGP)[4] and inves16 tigate its properties. The Facility for Antiproton and Ion Re17 search (FAIR)[5] in Germany will carry out high-luminosity 18 fixed-target heavy-ion collision experiments, exemplified by

Although high-energy facilities such as RHIC-STAR and FAIR-CBM effectively address physics topics such as 28 medium effects on hadron properties in dense matter, the 29 QCD phase structure in the high-baryon-density region, the 30 location of the critical point of the phase transition, and ex31 otic states of matter, they provide only limited access to the 32 region of relatively low temperature and high baryon chem33 ical potential. This region lies precisely within the core re34 search scope of the Heavy Ion Research Facility in Lanzhou35 Cooling Storage Ring (HIRFL-CSR)[7] and the High Inten36 sity Heavy Ion Accelerator Facility (HIAF)[8] in China. The 37 Low-Temperature High-Density Nuclear Matter Spectrome38 ter, namely the CSR External-target Experiment (CEE)[9], is 39 China' s first large-scale nuclear physics experiment operating ∗ This work was supported by the National Natural Science Foundation of 40 in the GeV energy regime. By performing nearly full-solidChina (12375193,12305210,12405229), the National Key Research and 41 angle measurements of particles produced in heavy-ion colDevelopment Program of China(2022YFF0503300, 2021YFA1601300). 42 lisions, the CEE aims to investigate the properties and com† Corresponding author, Hai-Bo Yang, yanghaibo@impcas.ac.cn. 43 plex structure of nuclear matter in the low-temperature, high26 international mainstream ZDCs (CBM-ZDC) typically adopt a single-anode readout scheme with external attenuators to 82 expand the dynamic range[6]. However, this approach of83 ten introduces additional noise and signal distortion, and the 84 switching response of mechanical/electronic attenuators can48 86 energy heavy-ion collisions.

To address these limitations, 50 Projection Chamber (TPC)[12, 13], inner and outer Time-of87 improve detector performance, and expand the measurement 51 Flight detectors (iTOF[14, 15] and eTOF[16, 17]), a Multi88 range, the PMT readout was modified from anode output to 52 Wire Drift Chamber (MWDC)[18, 19], and the Zero-Degree 89 dual-dynode output, and the PMTs were upgraded to Hama53 Calorimeter (ZDC)[20]. The outermost annular structure cor90 matsu R7525 and R3478 models (each with eight dynodes). 54 responds to the secondary magnet, with the heavy-ion target 91 After repeated testing and optimization for the required mea55 located 35 cm upstream of the magnet center. The TPC is po92 surement range, the third and sixth dynodes were selected as 56 sitioned at the geometric center of the magnet to measure the 93 the signal outputs, and the gain of the sixth dynode is approx57 trajectories of high-angle and low-momentum charged par94 imately 100 times that of the third dynode. The combination 58 ticles.

The iTOF surrounds the TPC and is used to mea95 of low- and high-gain outputs enables coverage of a wider 59 sure the time of flight of most particles detected by the TPC. 96 dynamic range.

In addition, the ZDC subsystem imposes 60 To enhance particle-identification capability in the forward97 stringent requirements on long-term stability in magnetic61 angle region, an MWDC array is arranged upstream of the 98 field environments. Under high count rates, both the read62 TPC along the beam direction to measure the trajectories of 99 out bandwidth of the 384 channels and the accuracy of of63 charged particles in the large-rapidity region, and an eTOF 100 fline analysis present significant technical challenges.

Ac64 detector is installed downstream. Particle mass determina101 cordingly, corresponding hardware upgrades and logic opti65 tion and species identification are achieved through time-of102 mizations were implemented in the detector electronics sys66 flight measurements. The ZDC is installed downstream of 103 tem, which was subsequently integrated with the CEE central 67 the eTOF, close to the beam line, and its primary function is 104 trigger, clock, and DAQ subsystems for full-system integra68 to determine the centrality of collision events and reconstruct 105 tion testing. System-level tests and verification were com69 the reaction plane. 106 pleted, demonstrating the excellent performance of the up70 71 sists of fan-shaped Plastic Scintillator (PS) bars, each of 72 which is directly coupled to a Photomultiplier Tube (PMT) 73 that converts the deposited energy of charged particles into II. THE ARCHITECTURE OF THE READOUT 74 electrical signals. Beam tests of the prototype ZDC within ELECTRONICS 75 the CEE energy range showed that nucleus-nucleus collisions 76 produce a large number of light nuclei and heavy ions, that

78 ZDC detection units, thereby generating intense optical sig- 111 ics system, which comprises 12 Front-End Cards (FECs), 12 79 nals that can easily saturate the PMT anode outputs. Notably, 112 Readout Control Units (RCUs), one sub-trigger module, one

density region. The expected results will deepen our understanding of frontier topics such as compact astrophysics, nu46 clear reaction dynamics, and the equation of state of nuclear 47 matter.

sub-DAQ module, and one sub-clock module. The FEC is 146 erates a stable global clock signal for all detector subsystems, responsible for receiving particle-hit signals from the PMTs, 147 and the CEE trigger subsystem[24] distributes global trigger, 115 where they are amplified and conditioned before being trans-148 synchronization, start, and stop commands to all detector sub116 mitted to the RCUs via shielded coaxial cables. The RCU 149 systems. 117 performs five main functions: first, digitizing the detector 118 signals from the FECs, extracting the required energy and 119 time information through FPGA-based data-processing algo150 A. The Design of the Hardware 120 rithms with online-configurable thresholds, and transmitting 121 the data to the CEE DAQ system via optical fibers in a speci151 The ZDC detector comprises a total of 384 readout chan122 fied format; second, receiving batch configuration informa152 nels, with 32 channels allocated to each independent FEC. To 123 tion from the CEE DAQ system[21] and decomposing, is153 avoid crosstalk between the saturated high-gain signals of the 124 suing, and executing control commands for the RCU; third, 154 6th dynode (DY6) and the low-gain signals of the 3rd dyn125 collecting board temperature and voltage information and re155 ode (DY3), the two types of signals are strictly assigned to 126 porting real-time status to the slow-control subsystem via the 156 different FECs. The FEC is based on a Charge-Sensitive Am127 CEE DAQ; fourth, receiving the global trigger signal from 157 plifier (CSA) architecture with discrete components, which 128 the sub-trigger unit, selecting valid events by calculating the 158 converts detector charge pulses into exponential voltage sig129 time difference between the global trigger and the internal 159 nals with a high signal-to-noise ratio, whose peak values are 130 self-trigger of the RCU, and executing global clock synchro160 proportional to the integrated input charge. The feedback ca131 nization and data acquisition start/stop commands through 161 pacitances of the DY3 and DY6 channels are 18 pF and 47 132 trigger-command parsing; and fifth, receiving the clock sig162 pF, respectively, with a shaping time of approximately 12 µs. 133 nal from the sub-clock unit, using it as the global clock of the 163 Overvoltage protection circuits are integrated into both the in134 RCU to achieve synchronization between the ZDC subsystem 164 put and output stages, and a test pulse port is provided for lab135 and the entire CEE system. 165 oratory calibration with a high-precision pulse generator. The The High-Voltage (HV) crate delivers 192 channels of high 166 FEC motherboard is installed in an aluminum shielding box 137 voltage to the PMT array through an HV divider unit and re- 167 to provide both electromagnetic shielding and radiation resis138 ceives control signals from the CEE slow control subsystem 168 tance. The as-

Figure 4

Figure 1: Figure 4

sembled module is inserted into the electronic 139 via Ethernet. The CEE slow control subsystem[22] is primar- 169 chassis as a whole, and the RCU supplies $±$3.3 V via coaxial 140 ily used to monitor in real time the voltages and temperatures 170 cables to ensure grounding integrity and interference immu141 of all CEE components, as well as to remotely control power 171 nity. The amplified 32-channel analog outputs are transmitted 142 supplies, signal sources, and oscilloscopes. The CEE DAQ 172 to the RCU via high-speed interboard connectors. 143 subsystem is responsible for configuring the parameters of all 173 144 detectors, transmitting and storing acquired data, and recon- 174 whose core components include a multi-channel analog 145 structing physical events. The CEE clock subsystem[23] gen- 175 conditioning circuit, two 16-channel, 14-bit AD9249[25]

Analog-to-Digital Converter (ADC) chips from Analog 200 data uplink. Two single-ended LEMO connectors are configDevices, each operating at 40 Mega Samples Per Sec- 201 ured for the trigger link: one for receiving the CEE system 178 ond (MSPS), one Xilinx Kintex-7 XC7K325T[26] field- 202 trigger signal, and the other for bidirectional trigger commu179 programmable gate array (FPGA), two configurable clock 203 nication between the DY6-RCU and DY3-RCU to achieve 180 chips (AD9512[27] and SI5338[28]), optical fiber interfaces, 204 timing alignment of the high-gain and low-gain sections. The 181 a power module, and various connectors. The multi-channel 205 RCU is powered by the +5 V, +3.3 V, and −5 V buses from the 182 analog conditioning circuit consists of low-noise operational 206 external chassis, with secondary power conversion provided 183 amplifiers and resistor-capacitor networks, which perform 207 by on-board DC-DC converters and Low-Dropout Regulators 184 linear conversion of single-ended exponential signals into dif- 208 (LDOs). Digital and analog power supplies are routed in sep185 ferential signals to match the input range of the ADCs. Under 209 arate areas with local shielding to ensure the long-term stable 186 FPGA control, the two AD9249 chips perform waveform dig- 210 operation of the RCU in strong magnetic fields and high count 187 itization and sampling synchronously with the system clock, 211 rate environments. 188 ensuring consistent sampling timing across all ZDC channels.

The clock system adopts an "external reference plus multiB. The Design of the Firmware channel synchronization" scheme: the 40 MHz clock signal 212 191 from the CEE clock subsystem is received via a differenFig. 4

shows the firmware block diagram of the RCU. From 192 tial LEMO connector and used as the global reference clock 213 193 for the FPGA logic, while the internal main clock is gen- 214 the perspective of the logical architecture, the firmware is 194 erated by the Phase-Locked Loop (PLL) in the FPGA; the 215 divided into two layers: the underlying driver and interface 195 AD9512 splits the 40 MHz main clock into two channels 216 modules and the functional modules for user configuration, 196 to provide synchronous clocks for the two ADCs, ensuring 217 collectively referred to as the user interface. The user inter197 inter-channel sampling jitter of less than 10 ps; the SI5338 218 face mainly consists of three "centers" : the Status Center, the 198 provides a 125 MHz low-jitter reference clock for the FPGA 219 Control Center, and the Data Processing Center. The underly199 GTX serial transceivers to support a 2.5 Gbps optical-fiber 220 ing driver/interface modules and the user interface are loosely

coupled and interconnected via three AXI-Stream buses (Sta- 244 tribution, and execution while supporting register status readtus Stream, Control Stream, and Data Stream), which enable 245 back to achieve closed-loop "command-feedback" manage223 the parallel execution of real-time status monitoring, configu- 246 ment. 224 ration command issuance and execution, and event frame as225 sembly and transmission, thereby significantly improving the 226 scalability and real-time performance of the system.

3. Data Processing Center

The Data Processing Center performs core tasks such as waveform digitization, feature extraction, trigger selection, 250 and event frame assembly, and is internally divided into an Using the Xilinx Analog-to-Digital Converter (XADC[29]) 251 algorithmic processing chain, a trigger selection chain, and a 229 embedded in the FPGA, the Status Center periodically ac- 252 parameter configuration chain. 230 quires the FPGA junction temperature and core voltage, as- 253 (1) Algorithm Processing Chain 231 sembles these data together with the status registers of key 254 The 32-channel, 14-bit serial data output by the AD9249 are 232 modules into a status frame, and transmits the frame to the 255 converted into 32-channel parallel data by the ADC driver 233 back-end slow control subsystem via the Status Stream at reg- 256 logic and then forwarded to the algorithm processing chain, 234 ular intervals; this frame is used for long-term stability moni- 257 first entering the rising-edge detection module. This mod235 toring and rapid fault localization. 258 ule adopts a dual-criteria mechanism of "threshold crossing 259 + slope" : if at least four of six consecutive sampling points 260 satisfy the monotonic increase condition, with each subse236

2. Control Center

261 quent value exceeding the preceding one, and all exceed the 262 set threshold, a valid rising edge is identified, a channel-level The Control Center consists of a Reset Management Mod- 263 self-trigger signal is generated, and the timestamp of the trig238 ule and a Command Configuration Module. The former cen- 264 ger moment is recorded. The channel threshold and the re239 trally manages external hard resets, soft resets, and local re- 265 quired number of threshold crossings can be dynamically ad240 sets of each submodule to ensure timing

safety during power- 266 justed via online configuration. To ensure waveform integrity, 241 on and reconfiguration; the latter caches configuration com- 267 a waveform delay buffer module is introduced, whose delay 242 mands issued by the DAQ in Block Random-Access Memory 268 period is matched to the processing time required for rising243 (BRAM), and performs command verification, parsing, dis- 269 edge detection, ensuring that subsequent processing is based

Status Center

on complete waveform segments. The delayed waveform data 328 channel ID, trigger time, and complete waveform data, and then enter the waveform screening module, which eliminates 329 the latter including only the channel ID, trigger time, and 272 events with saturation or an abnormal baseline by means of 330 peak information; the frame tail records the event-level trig331 ger time. The assembled event frame is temporarily stored in 273 baseline-range verification.

The screened waveforms enter the sampling module, which 332 the second-level buffer and transmitted to the DAQ interface 275 supports two sampling modes: "waveform" and "peak." In the 333 via the Data Stream bus before being forwarded to the CEE 276 full-waveform mode, the first 80 sampling points after trig- 334 DAQ system. 277 gering are continuously sampled at 25 ns intervals, and the 335 (4) Parameter Configuration Module 278 subsequent 19 points are sampled at 500 ns intervals, result- 336 System parameters are divided into two categories according 279 ing in a total of 11.5 µs of waveform data. Finally, a data 337 to the timing of configuration: one is "power-on-only"pa280 packet containing the channel ID, trigger time, and 99 sam- 338 rameters (e.g., sampling window length and self-trigger event 281 pling points is formed and written into the WAVE-FIFO first- 339 window), which are stored in registers and automatically 282 level buffer. In the peak mode, the waveform data are com- 340 loaded during system power-on or reset; the other is "online283 pared cycle by cycle within the 4 µs self-trigger window, the 341 modifiable" parameters (including data sampling mode, trig284 maximum value is extracted as the peak amplitude, and only 342 ger mode, channel threshold, multiplicity threshold, external 285 the channel ID, peak value, and trigger time are recorded and 343 trigger valid window, etc.), which are dynamically configured 286 written into the PEAK-FIFO first-level buffer. The peak data 344 by the DAQ through the Control Center before each acquisi287 are packaged before the end of the waveform falling edge, 345 tion. This architecture supports real-time adjustment during 288 which significantly reduces the required data bandwidth and 346 experiments without recompiling the firmware, thereby sig289 ensures dead-time-free channel acquisition. 347 nificantly improving the flexibility and maintainability of the (2) Trigger Selection Chain 348 system. 291 The RCU supports two trigger modes: "self-trigger" and 349 In summary, after hardware-based waveform digitization 292 "system trigger," which are applicable to independent ZDC 350 of detector signals, the ZDC electronics system adopts a 293 testing and full-system joint data acquisition in the CEE, re351 modular and pipelined algorithmic architecture at the logic 294 spectively. In the self-trigger mode, any channel that meets 352 level, enabling efficient online transformation from raw wave295 the rising-edge condition sets a channel flag, and a multiplic353 forms to physical event frames. It supports flexible switch296 ity decision is made based on the channel flags within the 354 ing between multiple trigger and data modes, meeting the 297 configurable self-trigger time window for a single event. If 355 bandwidth reduction requirements under high count rates 298 the multiplicity exceeds the preset threshold, an RCU-level 356 while ensuring the accuracy and integrity of offline analysis, 299 trigger is generated, and the inactive channels are automati357 thereby providing reliable online data-processing capability 300 cally masked until the end of the event. In the system-trigger 358 for the stable operation of the ZDC detector under various 301 mode, the system trigger signal is parsed by the Ex-trigger 359 operating conditions. 302 logic into four types of signals (Start, Stop, Sync, and System 303 Trigger): Start and Stop define the activation and deactiva304 tion of the system-trigger mode, and Sync resets the global 305 timestamp to achieve clock synchronization across multiple III. PRE-EXPERIMENT SYSTEM TESTS 306 boards. The System Trigger is the global trigger signal pro307 duced by coincidence logic: in cosmic-ray mode, it is gener308 ated from the coincidence trigger of iTOF and eTOF; in beam The ZDC readout electronics system has been fully inte309 mode, it is derived from the coincidence trigger of T0, iTOF, 362 grated with the detector hardware and installed in the CEE. 310 and eTOF. 363 The electronic chassis adopts a layered layout: the high311 Upon each arrival of a system trigger signal, the ZDC elec- 364 voltage divider module is placed on the top layer, and a 312 tronics opens a configurable trigger time window, reads the 365 forced-air cooling system is integrated into the chassis to en313 trigger timestamp from the first-level buffer, and immediately 366 sure long-term operational stability; the RCUs are arranged 314 marks the event as valid and forwards it to the event frame as- 367 on the outside to facilitate optical-fiber routing, and the FECs 315 sembly module if the trigger timestamp falls within the win- 368 are placed close to the detector to minimize the length of 316 dow; otherwise, the entire data packet is discarded and the 369 signal transmission cables, thereby reducing signal attenua317 system waits for the next trigger. In the self-trigger mode, 370 tion and electromagnetic interference. To comprehensively 318 external trigger validation is bypassed, and all events are un- 371 verify the performance reliability, environmental adaptabil319 conditionally marked as valid. 372 ity, and detector compatibility of the electronics system, sys373 tematic pre-experimental tests were carried out before the (3) Event Frame Assembly Chain 321 After trigger selection is completed, the system enters the 374 beam experiment, including electronics performance tests 322 event-frame assembly stage. The event frame adopts a uni- 375 and cosmic-ray tests. Each type of test was statistically an323 fied format consisting of a frame header, a data payload, and 376 alyzed using the eight sectors (rings) of the ZDC as the basic 324 a frame tail.

The frame header contains the frame length, 377 units (because the performance of channels within the same 325 trigger sequence number, and board ID; the payload con- 378 sector was highly consistent, one representative channel from 326 tains data from the WAVE-FIFO or PEAK-FIFO according 379 each sector was selected for presentation), laying a solid foun327 to the current sampling mode, with the former including the 380 dation for the subsequent beam experiment.

conditions. (d) INL values for each ring under different conditions.

were kept in a magnetically shielded area. A high-precision signal source was used to simulate the output pulse signals 404 of the detector. The magnetic-field intensity was increased Before the installation of mass-produced electronic compo405 in steps of 100 Gs, starting from 0 Gs (the zero-field ref383 nents, a systematic evaluation was carried out on the environ406 erence state), and the baseline characteristics and linear re384 mental robustness of the FECs and RCUs, focusing on ver407 sponse data at each field intensity were continuously collected 385 ifying their long-term operational stability under magnetic408 until the RCUs exhibited functional abnormalities. 386 field exposure and temperature-cycling conditions to ensure 387 that they meet the requirements of the complex environment The test results, as shown in Fig. 5 FIGURE:5, indicate that the 388 at the CEE. As shown in Fig. 5(a), the test platform uses a 410 electronic system maintained stable performance with no 389 high-precision signal source (Tektronix AFG3252C[30]) as 411 waveform distortion and no significant fluctuation in the base390 the signal source to generate exponentially decaying signals 412 line RMS[31] value at magnetic field intensities of 1200 391 with different amplitudes and frequencies, thereby simulat413 Gs and below. As presented in Fig. 5(c), the linear fitting 392 ing the actual pulse signals of the detector, which are then fed 414 curve was basically consistent with that obtained in the non393 into the test port of the FEC. The electronics system is set to 415 magnetic state, demonstrating a good linear response. 394 self-trigger mode. The test signals are amplified by the FEC, 416 shown in Fig. 5(d), the integral nonlinearity (INL) was below 395 transmitted to the RCU for digitization and algorithm pro417 0.3% in the non-magnetic condition and slightly increased to 396 cessing, then sent to the DAQ via optical fibers, and finally 418 0.3%-0.4% at a magnetic field intensity of 1200 Gs, both of 397 the data are analyzed offline using ROOT software to obtain 419 which were far lower than the system design threshold (1%). 398 the corresponding test results. 420 When the magnetic field intensity exceeded 1300 Gs, abnor421 mal fluctuations in the power supply current occurred, the 422 RCU fiber connection was interrupted, and the module failed

1. Magnetic Field Environment Test

423 to work normally. These results show that the ultimate mag424 netic field tolerance threshold of the system is approximately The FECs and RCUs were placed in a controlled 425 1200 Gs, which fully meets the magnetic field environment 401 electromagnetic-field environment, while the other modules 426 requirements ($ $200 Gs) of the CEE experimental site.

Electronics Performance Test

All 12 FECs and 12 RCUs were placed in a high- and low- 480 responding to 0.25 mV (the ordinate represents the RMS 481 value, and the abscissa represents the representative channel 429 temperature test chamber (model TL-1D-70-F), and a high482 for each ring).

Based on the statistical results of approxi430 precision signal source was connected via cables to simulate 483 mately 860,000 cosmic-ray events, the baselines of all eight 431 the detector output signals. A high- and low-temperature cy ◦ 484 sectors remained stable, and the noise RMS of all channels 432 cling test was performed over the temperature range of 0 C 485 was below 4 ADC LSBs (equivalent to less than 1 mV). This 433 to 45 C, with a single-cycle duration of 525 minutes (240 486 confirms that the high-voltage bias network is highly compat434 minutes each for the high- and low-temperature stages and 487 ible with the electronics system and does not introduce addi435 a temperature change rate of 2 C/minute), and a total of 14 488 tional noise, thereby meeting the system noise specifications. 436 complete cycles was completed. The baseline stability and 437 linearity data under extreme high- and low-temperature con438 ditions were collected for each cycle.

The test results, as shown in Fig. 5(b), show that in the 440 temperature range of 0 C to 45 C, the noise RMS value of

2. Waveform Acquisition Test

441 each channel fluctuated between 1.6 and 2.5 ADC Least Sig442 nificant Bits (LSBs). The RMS value was slightly lower at 443 0 C (1.6 2.0 ADC LSBs) and increased slightly at 45 C To verify the correctness and consistency of waveform ac444 but still remained within a stable range, indicating excellent 491 quisition for each channel in the electronics system, after one 445 noise stability. The linear fitting results in Fig. 5(c) reveal that 492 week of cosmic-ray testing, waveform data from all chan446 the ADC output value had a good linear relationship with the 493 nels were extracted, superimposed, and analyzed using ROOT 447 input voltage, and the fitting curves at different temperature 494 software.

The waveform superposition results of a typical 448 points basically coincided. As shown in Fig. 5(d), the inte495 channel from one data file (Fig. 6 FIGURE:6) show that all wave449 gral nonlinearity (INL) was far lower than the system design 496 forms were triggered at the preset threshold, with complete 450 threshold (1%). 497 waveform shapes, stable peak values, no obvious distortion The above results confirm that the electronic system has a 498 or drift, and good consistency across channels. This confirms 452 stable linear response capability within the experimental tem499 the reliability of the electronics system in waveform mode, 453 perature and magnetic field ranges, meeting the environmen500 which can accurately capture the detector output waveforms 454 tal adaptability requirements of the front-end electronics of 501 and provide highquality raw data for subsequent data pro455 the detector. 502 cessing, such as pulse-shape discrimination (PSD[33]) and

Temperature Cycle Reliability Test

energy extraction.

Cosmic Ray Test

Cosmic-ray tests were conducted to verify the overall performance of the integrated ZDC electronics and detector and 504

3. Coincidence Trigger Matching and Track Verification

459 to perform system-level calibration through 48 hours of con460 tinuous cosmic-ray data acquisition, including the evaluation The ZDC electronics adopts a combined "system-trigger 461 of baseline stability, waveform acquisition integrity, trigger506 + self-trigger" matching mechanism. In the cosmic-ray test 462 matching effectiveness, and energy-measurement resolution. 507 mode, the system trigger signal is generated by the coinci508 dence of eTOF and iTOF and distributed to the ZDC subsys509 tem by the CEE trigger system. Due to the fixed transmission

1. Noise Test

510 delay between the incidence of a cosmic ray on the ZDC de464 After the integration of the ZDC electronics and detec- 511 tector and the reception of the system trigger signal by the 512 electronics, it is necessary to verify the effectiveness of the 465 tor, the RC effect introduced by the PMT high-voltage bias 513 trigger-matching time window. 466 network at the output stage shifts the DC operating point

of the front-end amplifier, resulting in a difference between 514 The test results show that the time difference between the the baseline level under high-voltage operation and that ob- 515 system-trigger time and the self-trigger time is concentrated 469 served in standalone electronics tests. Meanwhile, random 516 around 2.2 µs (Fig. 7 FIGURE:7, with a small dispersion (standard de470 pulses generated by the continuous incidence of cosmic rays 517 viation $ $0.1 µs). Fig. 7(b)Visual verification of cosmic-ray 471 can cause directly sampled baseline values to be contami- 518 tracks was performed using the CEE event display software, 472 nated by real signals.

Therefore, during the 48-hour con- 519 and the observed cosmic-ray tracks corresponded accurately 473 tinuous cosmic-ray data acquisition, the following baseline- 520 to the trigger timing, with no missed or false triggers. This 474 estimation method was adopted: the mean value of the first 521 confirms that the current trigger-matching time window can 475 20 points among the 40 samples preceding the threshold- 522 effectively capture physical events induced by cosmic rays 476 crossing point of each waveform was calculated as the base- 523 and that the trigger logic design is reasonable, thereby meeting the timing requirements of joint system acquisition. line estimate for that waveform.

Cosmic Ray Energy Spectrum Test

the system energy-response behavior was verified through cosmic-ray energy-spectrum tests. The waveform peaks ex-

The reliability of energy measurement is one of the key performance metrics of the ZDC, and the correctness of

tracted from the 48-hour cosmic-ray data were statistically Figure 10 [FIGURE:10] shows the energy spectra of the ZDC detector unanalyzed to obtain the cosmic-ray energy-spectrum distribu- der the two acquisition modes in the heavy-ion beam-target tion (Fig. 8 [FIGURE:8]). This distribution is well described by a Landau experiment. The eight subplots represent the module-level function, which is consistent with the energy-loss behavior energy spectra of the eight sectors (ring 0 to 7). It can be of cosmic-ray muons passing through the plastic scintillator seen that the spectral shapes and peak positions are consistent (PS). The fitting results show that the energy resolution is less under the two modes, and the spectral contours of each sec than 9.7%, thereby satisfying the system requirement for en- tor show no obvious distortion, reflecting good performance consistency of the detector and electronics system across dif ergy resolution ($\Delta E/E \leq 15\%$). ferent channels. Moreover, signals from nucleons and nuclear fragments with charge numbers $Z = 1$ 6 can be clearly IV. EXPERIMENTAL RESULTS AND DISCUSSION distinguished.

For the convenience of energy calibration, the detector was translated 10.9 cm to the right to align the innermost ring After completing the electronics performance tests and cosmic-ray tests, the ZDC system carried out its first full- module with the beam center, allowing the carbon beam to system beam experiment at the CEE terminal in December directly irradiate the detector. The measurement results are The experiment adopted a configuration in which a shown in Fig. 11 FIGURE:11: the carbon nucleus ($Z = 6$) peak ap carbon (C) beam impinged on carbon and lead targets (C/Pb), pears as the highest-intensity characteristic peak in the energy with a beam duration of 20 days and a peak energy of 1.1 spectrum, and the energy spectra in peak mode and waveform GeV. The ZDC electronics system operated stably in both mode are fully consistent. This verifies the equivalence of peak and waveform modes, accumulating a large number of the two acquisition modes under direct beam incidence and valid events and successfully verifying multiple performance confirms the operational stability of the system at high beam metrics, thereby further confirming the reliability and practi- intensities.

Charge peaks of nucleons and nuclear fragments from $Z =$ cality of the system in real experimental conditions. 1 (proton) to $Z = 6$ (carbon nucleus) can be clearly resolved under both modes, confirming that the ZDC system can effec604 tively identify forward particles with different charge num550 A. Stability Verification 605 bers. Double-Gaussian fitting was performed on the peak551 During the beam experiment, the system was switched to 606 mode energy spectra of all channels (Fig. 11(b) shows the fit607 ting results of all rings), indicating that the energy resolution 552 waveform mode daily to collect baseline data, and the base608 is better than 15%, which meets the system design require553 line mean was calculated from these data. The baseline drift 609 ment (ΔE/E ≤ 15%). 554 of the 3rd dynode (DY3, low gain) and the 6th dynode (DY6, In summary, the good consistency of the energy spectra 555 high gain) was monitored in particular to verify the stability 611 between waveform mode and peak mode indicates that both 556 of the electronics system and detector under high-count-rate 612 sampling modes operate reliably and can be flexibly selected 557 and long-term operating conditions.

The test results are shown in Fig. 9 [FIGURE:9], which presents the 613 according to experimental requirements: peak mode can ef614 fectively reduce the data bandwidth and is suitable for high559 DY6 and DY3 baseline-time curves of representative chan560 nels from eight sectors (one channel per sector).

The re- 615 count-rate experimental scenarios, whereas waveform mode 616 retains complete pulse-waveform information and provides 561 sults show that, throughout the entire 26 baseline acquisitions 617 data support for subsequent offline analysis, such as Pulse562 throughout the beam time, the baseline drift of all channels 618 Shape Discrimination (PSD) and discrimination between neu563 was less than 1 mV, with no obvious fluctuations or abrupt 619 trons and charged particles.The energy-spectrum test results 564 changes. This indicates that the noise level of the electron620 obtained under direct carbon-beam irradiation of the target 565 ics system is stable, the detector gain exhibits no observable 621 further verify the reliability of the ZDC system' s response 566 drift, and the high-voltage bias network and front-end elec622 to high-energy beams, and the symmetric peak profiles and 567 tronics have good long-term operational reliability, thereby 623 stable resolution provide accurate energy data for the mea568 meeting the requirements of the beam experiment for long624 surement of collision-event centrality and reaction-plane re569 term, high-stability operation. 625 construction in the CEE. The specific physics analysis results 626 will be presented in a subsequent paper.

Peak and Waveform Mode Beam Energy Spectrum

CONCLUSION

Energy measurement is a core function of the ZDC detecThis work presents the completion of the hardware up573 tor. In the beam experiment, data were collected in peak mode 628 574 (PEAK) and waveform mode (WAVE), respectively, and the 629 grade, firmware optimization, and system integration of the 575 beam energy spectra were obtained by combining channel 630 CEE ZDC readout electronics system. The performance, reli576 data after time alignment and gain correction to verify the 631 ability, and stability of the system were comprehensively ver577 energy-measurement accuracy and particle-identification ca-632 ified through electronics performance tests, cosmic-ray tests, 578 pability of the system. 633 and beam experiments.

The optimized ZDC readout elec572

tronics system achieves excellent core performance metrics: 635 the noise RMS of all channels is <1 mV, the INL is <0.4%,

and it operates stably over extended periods under magnetic 650 heavy-ion collisions, thereby providing reliable data for the fields of 1200 Gs and below and within the temperature range 651 measurement of collision-event centrality and reaction-plane 638 of 0 C–45 C, demonstrating environmental adaptability that 652 reconstruction. The modular and pipelined firmware archi639 meets the requirements of the CEE. Cosmic-ray tests confirm 653 tecture of the electronics system enables efficient signal ac640 that the system has stable baselines, complete waveform ac- 654 quisition and processing and supports multiple sampling and 641 quisition, accurate trigger matching, and an energy resolution 655 trigger modes. It not only meets the bandwidth-compression 642 of $ $15%. They also demonstrate that the detector and elec- 656 requirement under high count rates but also ensures the accu643 tronics system are well integrated without introducing addi- 657 racy and integrity of offline analysis, thereby fully satisfying 644 tional noise or signal distortion. During the 20-day continu- 658 the physics requirements of the CEE for the ZDC detector. 645 ous beam experiment, the system operated stably in both peak 646 and waveform modes, with a baseline drift of less than 1 mV, 647 successfully reconstructing the charge peaks of Z=1-6, and VI. BIBLIOGRAPHY 648 maintaining an energy resolution of less than 15%. It can ac649 curately measure the energy of forward particles produced in

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Figure 1

Figure 2: Figure 1

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Figures

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