Development of a MWDC prototype of the CSR external-target experiment

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Abstract

The cooling storage ring (CSR) external-target experiment (CEE) is a spectrometer used in construction to study the properties of nuclear matter in high-baryon density regions at the Heavy-Ion Research Facility in Lanzhou (HIRFL). This study presents the design, simulation, manufacturing, and testing of a half-size prototype of a multi-wire drift chamber (MWDC) for the CEE. First, the performance of the MWDC connected to home-made electronics was simulated. The results demonstrated that an energy resolution of 18.5% for 5.9-keV X-rays and a position resolution of 194 um for protons can be achieved by the current design. Because the size of the largest MWDC reached 176 × 314 cm, a set of 98 × 98 cm prototypes was built using the new techniques. The positioning accuracy of the anode wires in this prototype exceeded 20 um. After optimization using commercially available electronic devices, the prototype achieved an energy resolution of 19.7% for a 55Fe X-ray source. The CEE-MWDC detector and electronics were simultaneously tested. An energy resolution of 22% was achieved for the 55Fe source; the track residuals were approximately 330 um for the cosmic rays. The results demonstrate that the current design and techniques meet the requirements of the CEE-MWDC array.

Full Text

Preamble

Development of a MWDC Prototype for the CSR External-Target Experiment

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The Cooling Storage Ring (CSR) external-target experiment (CEE) is a spectrometer under construction at the Heavy-Ion Research Facility in Lanzhou (HIRFL) for studying the properties of nuclear matter in high-baryon-density regions. This study presents the design, simulation, manufacturing, and testing of a half-size prototype of a multi-wire drift chamber (MWDC) for CEE. First, the performance of the MWDC connected to home-made electronics was simulated, demonstrating that an energy resolution of 18.5% for 5.9-keV X-rays and a position resolution of 194 µm for protons can be achieved with the current design. Because the largest MWDC reaches 176 × 314 cm, a set of 98 × 98 cm prototypes was built using new techniques. The positioning accuracy of the anode wires in this prototype exceeded 20 µm. After optimization using commercially available electronic devices, the prototype achieved an energy resolution of 19.7% for a ^{55}Fe X-ray source. The CEE-MWDC detector and electronics were simultaneously tested, achieving an energy resolution of 22% for the ^{55}Fe source and track residuals of approximately 330 µm for cosmic rays. These results demonstrate that the current design and techniques meet the requirements of the CEE-MWDC array.

Keywords: CEE, MWDC, Garfield++, ^{55}Fe source, Position resolution

INTRODUCTION

Heavy-ion collision experiments are conducted to study the equation of state of nuclear matter (nEOS). Compressed nuclear matter beyond saturation density can be created in the energy region ranging from hundreds of MeV/u to 1 GeV/u, and constraints on the nuclear matter EOS can be determined using observables identified in heavy-ion experiments. Several such experiments have been operated or are currently running worldwide. The Cooling Storage Ring (CSR) at the Heavy-Ion Research Facility in Lanzhou (HIRFL) provides beams from proton to uranium with maximum energies of 2.8 GeV/u and 0.5 GeV/u, respectively [1–3]. In this energy region, nuclear stopping—defined as the ratio of transverse to longitudinal energy of products in central heavy-ion collisions—reaches a maximum plateau, offering a valuable opportunity to study the nEOS at approximately twice the saturation density [4, 5].

To utilize the beam conditions of the machine, the HIRFL-CSR external-target experiment (CEE) [6] was constructed in 2020 as a multi-purpose spectrometer covering the entire solid angle in the center-of-mass frame. It is designed to study the nEOS by measuring the phase-space distribution of light-charged particles, flow observables, meson production, and correlation functions [7, 8]. Similar to many spectrometers worldwide, the key components of CEE include tracking detectors placed in a magnetic field. In the forward region, the tracking array consists of three multi-wire drift chambers (MWDCs) that record hits from tracks emitted in the angular range from 5° to [Figure 1: see original paper] and Table 1 summarize the CEE requirements for the MWDCs and the achievements of the prototype.

In fixed-target experiments, the collision products of CEE are dominant in the forward region, so particle identification (PID) capability in the forward hemisphere of the laboratory frame is critical. Although the TPC can measure tracks with relatively good momentum resolution, its efficiency and resolution in the forward region are insufficient [6]. Therefore, a complementary tracking array consisting of MWDCs in the forward region is proposed due to its many advantages, including cost-effectiveness, good position resolution, and high allowable count rate. To maximize the acceptance of the MWDC array, the CEE spectrometer is equipped with three sets of MWDC detectors, two of which are placed within the dipole field. The beam passes directly through the central area of all three MWDC sets. Figure 1: see original paper presents the design of the MWDC array. MWDC1, MWDC2, and MWDC3 have dimensions of 93 × 166 cm, 128 × 230 cm, and 176 × 314 cm, respectively. Because the fabrication process and techniques for such large drift chambers must be validated, a 98 × 98 cm prototype set with 384-channel readout was developed, utilizing several practical designs to verify the feasibility of building a large MWDC.

The electronics used for the MWDC detectors were developed in-house. FEAM chips were employed in the integrated front-end electronics (FEE) to amplify and shape input signals, while switched capacitor array (SCA) boards were developed to sample and digitize waveforms. To avoid data congestion, the MWDC readout system utilizes FPGAs to fit waveform data online in real-time and extract time and energy information.

III. PERFORMANCE SIMULATION OF THE CEE-MWDC PROTOTYPE

A. Garfield++ Simulation Framework

To verify the performance of the entire system, detailed simulations were conducted using the Garfield++ software [25], considering both detector structure and front-end electronic responses. Garfield++ is dedicated software for simulating gas and semiconductor detectors that can model particle-gas interactions, electron and ion drift processes in gases, and electron avalanche multiplication under strong electric fields. By simulating electron and ion drift, induced currents can be generated at corresponding electrodes, and a near-real signal waveform is computed by applying the transfer function of the front-end electronics to these induced currents. The entire procedure integrates multiple programs, including HEED [26] to simulate interactions between radiation and gas, and Magboltz [27] to simulate macroscopic parameters of electron transport in gas, such as drift velocity and Townsend coefficient. The simulation includes three methods for electron and ion transport: Runge-Kutta-Fehlberg integration, Monte Carlo integration, and avalanche microscopy. Both Runge-Kutta-Fehlberg and Monte Carlo integrations rely on macroscopic parameters of electron transport simulated by Magboltz when modeling electron transport paths and avalanche amplification. To accurately simulate electron trajectories in small-scale structures (with characteristic dimensions comparable to the electron mean free path) and for detailed calculations of ionization and excitation processes, microscopic tracking of electrons is simulated using avalanche microscopy, which models microscopic collisions of electrons with atoms to obtain electron drift paths and avalanche processes. The collision simulations are based on cross-section data for electron scattering processes in MediumMagboltz (Magboltz 11.17 [28] contains all relevant cross-sections of electron-matter interactions).

B. Simulation of Energy Resolution

1. Simulation Process [Figure 2: see original paper] shows the spatial paths of conductive (primary) electrons generated by absorption of a 5.9-keV X-ray in argon atoms of the gas mixture (only one event is displayed as an example). Because the MWDC consists of numerous drift cells, a simplified model was used for performance simulations that retains the windows and wires of adjacent cells to simulate the signal generation process of a single cell. This approach can extract relevant amplitude and time information from signal waveforms to obtain the energy and position resolutions of a single drift cell. The prototype cell size was planned to be 10 × 10 mm, so the simulated drift cell model was set to 10 × 10 mm with cathode wire spacing of 2.5 mm.

The 5.9-keV X-rays from a ^{55}Fe source are commonly used to test the energy resolution of gas detectors with amplification. The HEED program was used to simulate the ionization-excitation process of 5.9-keV X-rays with the working gas. An example of the spatial position distribution of primary electrons produced by 5.9-keV X-ray absorption is shown in [Figure 2: see original paper]. The reaction produces one photoelectron at 2.694 keV, one Auger electron at 2.709 keV, and two Auger electrons at 0.217 keV [29]. These electrons continue to ionize the gas, producing secondary electrons. The spatial distribution of primary electrons is generally within 200 µm. The AvalancheMicroscopic method was used to simulate electron drift and avalanche processes, while Monte Carlo integration simulated ion transport. Combining these methods accurately models charge transport. Precise simulation of the electron avalanche process and electron/ion transport improves the accuracy of simulated electrode-induced currents. The following gas parameters were set in the simulation: composition of 20% CO_2 and 80% Ar, air pressure of 0.85 atm (matching local air pressure), and temperature of 25°C (matching ambient temperature). Important parameters of the CEE-MWDC electronic system are listed in Table 1. The induced current on the anode must be convolved with the transfer function of the front-end electronics (FEE) to obtain the final signal waveform. A pulse generator signal was fed into the FEE, and the oscilloscope sampled the FEE output waveform. The Garfield++ software reads this output waveform file and calculates the transfer function of the front-end electronics.

2. Simulation Results The signal waveform of a 5.9-keV X-ray captured by the oscilloscope is shown in Figure 3: see original paper, while the Garfield++ simulated waveform is shown in Figure 3: see original paper, which superimposes baseline noise with a peak-to-peak value of approximately 10 mV. A total of 6000 signal waveforms of 5.9-keV X-rays were simulated to obtain the energy spectrum, shown in Figure 4: see original paper. These X-rays were uniformly incident on the drift cell along the anode wire direction. The anode voltage was +1500 V, while cathode and field wires were at 0 V. The full-energy peak of the spectrum was 209.5 mV with an energy resolution of approximately 18.5%, meeting CEE requirements. The energy resolution includes contributions from fluctuations in primary ionization, avalanche amplification gain, and noise with a peak-to-peak value of 10 mV.

The experimental spectrum from the ^{55}Fe source test is shown in Figure 4: see original paper. Experimental results were apparently worse than simulation, primarily because the simulation was more ideal. In reality, surface inhomogeneity of the MWDC anode wire, nonlinearity of the electronic system, and SCA waveform sampling frequency reduced energy resolution to some extent. Additionally, experimental noise was greater than in simulation, and significant cosmic-ray background was present in the experimental energy spectrum compared to simulation.

The anode signal amplitude and electron avalanche gain were simulated as functions of operating voltage, as shown in Figure 4: see original paper. Gain and amplitude increased with voltage, with the rate of increase becoming more pronounced at high voltages. Simulation results generally agree with experimental results.

C. Simulation of Position Resolution

First, electron-drift isochrones of the drift cell structure were simulated, as shown in Figure 5: see original paper. Generally, if electron drift isochrones are closer to circular, the detector's position resolution will be better; however, the final position resolution is determined by the detector connected to the electronics. Position resolution simulation conditions were set identically to energy resolution simulations. The prototype position resolution was simulated for muons with momentum ranging from 1 GeV/c to 1 TeV/c at a detector operating voltage of 1550 V. Muon incidence angles were uniformly distributed from 0° to 30°. Approximately 20,000 effective muon tracks were randomly generated. The signal waveform generated after each muon crossed the drift cell was simulated, and the electron drift-time spectrum for all muons was obtained using the constant fraction timing method with a trigger ratio of 0.5, as shown in Figure 6: see original paper. A Fermi–Dirac function fitted the leading edge of the drift time spectrum to obtain the electron drift starting time (T_0) [30]. Electron drift time (T) was calculated relative to T_0. The distance (R) from the muon track to the anode wire is a known input parameter. The R-T function was obtained by creating an R-T correlation plot of all muon tracks and performing a fit. The R-T correlation plot for six incidence angle intervals is shown in Figure 6: see original paper, and the fitted R-T function is shown in Figure 6: see original paper. Simulation results demonstrate significant differences in RT functions corresponding to different angles beyond 50 ns. The simulated electron drift time (T) of each track was incorporated into the R-T relationship to obtain the fitted spatial distance (R_{fit}). The difference between R_{fit} and the real track-to-anode-wire distance (R) is the track residual. The distribution of track residuals for approximately 20,000 muons is shown in Figure 6: see original paper. Typically, MWDC position resolution significantly deteriorates when charged particles pass near the anode wire or drift-cell boundaries. Therefore, the residual distribution was fitted with a double Gaussian function [31], yielding a position resolution of 348 µm.

The prototype position resolution was also simulated for protons with momentum ranging from 0.1 to 10 GeV/c at a detector operating voltage of 1400 V. As shown in Figure 6: see original paper, the position resolution (sigma) was 194 µm, satisfying CEE requirements. The CEE-MWDC position resolution for protons was significantly better than for high-energy muons because primary electrons produced by proton ionization in the gas are more uniform and regular. Although the position of proton primary electrons has less negative impact, the proton signal waveform is more ideal.

IV. DEVELOPMENT OF CEE-MWDC PROTOTYPE

A. Design Details

To maximize reception of reaction products by the MWDC array, the CEE spectrometer uses three sets of MWDC detectors through which the beam passes directly at the center. To maintain the same acceptance, the size of the chamber farthest downstream from the target is 176 × 314 cm, requiring further exploration of the process for creating such large drift chambers. To test performance and compare with simulation results from Section 2, a 98 × 98 cm prototype set was designed and built to verify the large drift chamber construction process. As shown in Figure 7: see original paper, the detector includes X, U, and V measurement layers, an entrance window, and an exit window. The windows consist of 50-µm-thick double-sided aluminum-coated Kapton foil. Each measurement layer includes two anode wire layers and three cathode wire layers. To measure three-dimensional particle tracks, the wires of the X, U, and V layers are oriented vertically, at -30° to the X-layer wires, and at +30° to the X-layer wires, respectively. For each wire direction, to discriminate left and right positions, anode wires in two adjacent layers are displaced by 5 mm. For ease of fabrication and maintenance, the X, U, and V layers are completely independent and can be assembled into a complete detector using a sealing ring. Additionally, to minimize maintenance costs, each measurement layer features a partitioned structure. As shown in Figure 7: see original paper, the sensitive area of the X-measurement layer is divided into four zones, with completely independent mechanical, PCB, and signal lead components for each partition.

Figure 7: see original paper shows the cross-section of the X-measurement layer. Each measurement layer consists of four main parts: a bottom support frame, bounding wall, layer-spacing control pad, and PCB. For large MWDCs, resolving structural deformation caused by significant wire tension is essential. Therefore, a 20-mm-thick aluminum alloy was used as the support frame in the prototype to avoid significant wire tension reduction. The bottom support frame contains high-precision peg-holes for PCB positioning. Layer-spacing control pads ensure the spacing accuracy of each wire layer. The anode is a gold-plated tungsten wire with 20 µm diameter and 55 g tension. Field and cathode wires consist of gold-plated beryllium copper with 100 µm diameter and 150 g tension. The drift cell size is 10 × 10 mm. Figure 7: see original paper presents a photograph of the MWDC prototype interior.

B. Measurement of Anode-Wire Position Accuracy

The anode-wire position accuracy was measured after prototype fabrication. The wire-spacing measurement device is shown in Figure 8: see original paper, consisting primarily of an optical microscope, a stepping motor to control microscope movement, and a grating scale (resolution better than 1 µm) for accurate microscope position measurement. Figure 8: see original paper presents the anode-wire spacing distribution for the three prototype layers, with standard deviations of 19.9 µm, 17.89 µm, and 14.22 µm, respectively. The gradual reduction in standard deviation resulted from progressive optimization of the production process.

V. MEASUREMENT AND OPTIMIZATION OF THE 55FE ENERGY SPECTRUM

A. Distortion of the 55Fe Energy Spectrum

The 5.9-keV X-rays produced by ^{55}Fe are commonly used to test the energy resolution of gas detectors with amplification. After CEE-MWDC prototype construction, the 5.9-keV X-ray energy spectrum was first measured using commercial electronics manufactured by ORTEC [32], including a 142PC charge-sensitive preamplifier, 572A main amplifier, and ASPEC-927 multichannel analyzer (MCA). The detector operated in flow mode with gas composition of 20% CO_2 and 80% Ar at approximately 850 mbar pressure. The detector anode voltage was +1400 V, with field and cathode wires grounded. A typical 5.9-keV X-ray energy spectrum from the anode wire layer adjacent to the exit window is shown in Figure 9: see original paper. The energy spectrum from the anode wire layer adjacent to the entrance window exhibited an even more unusual shape, as shown in Figure 9: see original paper.

The electric field of the simplified MWDC prototype structure was simulated using COMSOL [33], as shown in Figure 10: see original paper. Simulation conditions were: field wires, cathode wires, and windows grounded; anode operating voltage of +1400 V. Results indicated electric field intensity of approximately 50 V/cm in the region between the U-layer cathode and entrance window, and approximately 20 V/cm between the V-layer cathode and exit window. The 5.9-keV X-rays ionize gas in the cathode-window region, producing primary electrons. Due to the leaking electric field in this region, some electrons drift toward the anode wire and generate undesired signals that distort the energy spectrum. Primary electrons generated between the cathode and window drift to the anode wires, negatively affecting both energy and position measurements of the MWDC.

B. Optimization of the 55Fe Energy Spectrum

A method that perfectly resolves electric field leakage without changing the electric field inside the drift cell was implemented to solve the ^{55}Fe energy spectrum distortion problem. By changing the electrode voltage configuration from an anode-wire voltage of +1400 V and cathode/field wires at 0 V to an anode-wire voltage of +1100 V and cathode/field-wire voltage of -300 V, the electric field was optimized. Simulation results for the optimized electric field are shown in Figure 10: see original paper, where electric field lines in the region between the cathode and window are directed from the window to the cathode. Ionized electrons drift to the window while ions drift to the cathode wire. Another approach to eliminate undesired signals is adding a guard wire layer maintained at positive voltage; however, for large MWDCs, this has two disadvantages: increased construction workload and greater wire tension requirements for the detector structure.

The ^{55}Fe energy spectrum measured after optimizing the voltage configuration is shown in Figure 9: see original paper. The energy spectrum measured by the MWDC improved significantly after voltage configuration optimization. Additionally, each MWDC cell has distinct boundaries that benefit overall detector performance.

C. Experimental Verification of Distortion and Optimization Mechanisms

To further verify that energy spectrum distortion is caused by the photoelectric effect of 5.9-keV X-rays with gas outside the drift cell, a guard wire was placed between the detector window and cathode wire for testing. As the guard wire voltage gradually changed from 0 V to -300 V, the main peak of the energy spectrum gradually increased. This was attributed to ionized electrons external to the drift cell: 5.9-keV X-rays interacting with gas between the cathode and guard wires produce primary electrons, some of which drift to the anode wire and generate signals. The X-ray count between the cathode and guard wires is significantly higher than inside the drift cell. As guard wire voltage changed from 0 V to -300 V, electric field intensity in the region between guard wire and cathode wire layers gradually increased, directed toward the guard wire. As more electrons reached the anode wire, the corresponding main peak of the energy spectrum gradually increased.

As shown in Figure 11: see original paper, when the guard wire voltage gradually changed from 0 V to +300 V, the electric field strength between the guard wire and cathode wire layers gradually decreased to zero, then gradually increased. At +300 V guard wire voltage, the electric field pointed toward the cathode wire layer, and ionized electrons drifted toward the guard wire. Therefore, as guard wire voltage changed from 0 V to +300 V, it became more difficult for ionized electrons between the guard wire and cathode wire to drift to the anode wire, reducing undesired signals.

This study provides a reference for electrode voltage configurations in space-limited wire-chamber detectors. Typically, wire chambers rely on dense cathode wires as boundaries for the sensitive volume. However, this study found that when the distance between the window and cathode is small, electric field intensity between the window and cathode wires increases, making cathode wires ineffective as sensitive volume boundaries and deteriorating detector performance. This study proposes a corresponding solution: setting the cathode to negative voltage causes electrons between the cathode and window to drift toward the window, allowing the cathode wire to form an effective boundary of the sensitive volume. These results also provide a useful reference for designing wire chambers to measure particle deposition energy (dE). For dE/dx measurements, both particle energy deposition (dE) and path length (dx) must be clearly defined.

VI. JOINT TESTING OF THE CEE-MWDC DETECTORS AND ELECTRONICS

A. Position Resolution with Cosmic Rays

The CEE-MWDC detector and electronics were jointly tested to verify that performance met CEE requirements. The system comprised 384 detector channels and 192 electronics channels. The detector had six anode wire layers, with 32 channels selected from each layer for signal input to the electronics. Therefore, the six anode wire layers overlapped an area of approximately 800 cm^2. A block diagram of the electronics used in the experiment is shown in Figure 12: see original paper. Two scintillation detectors were placed before and after the MWDC, with coincident signals used as triggers for SubDAQ. Scintillation detector signals were shaped using an OCTEC 460 amplifier, and waveforms were sampled using the SCA to obtain more accurate relative time-zero values.

The residual distribution of experimentally measured cosmic-ray tracks is shown in Figure 12: see original paper, with a sigma value of 330 µm. Joint test results demonstrate that the scheme satisfies CEE spectrometer requirements.

B. Energy Resolution with the 55Fe Source

The energy spectrum of the ^{55}Fe source was measured using the CEE-MWDC prototype detector with electronics. As shown in Figure 4: see original paper, the energy resolution (FWHM) was approximately 21.3%. Anode signal amplitudes were measured at different detector operating voltages, as shown in Figure 4: see original paper. Due to certain uncontrollable factors, differences between experimental and simulation results were observed. The energy-resolution (FWHM) distributions for the 32 FEE channels are shown in Figure 12: see original paper, with a mean value of 22%. Gain uniformity is illustrated in Figure 12: see original paper, which was less than 4%.

VII. CONCLUSION

This study presents Monte Carlo simulation programs based on Garfield++ to simulate the energy and position resolution performance of drift chambers. The program accurately simulates particle ionization processes in gas, electron and ion transport, and induced signal generation at electrodes. The anode-induced current was convolved with the transfer function of specific front-end electronics, producing simulated signal waveforms closely matching experimental waveforms. Amplitude and time information can be extracted from simulated waveforms to analyze MWDC energy and position resolution performance. The program provides references for drift cell design and setting important front-end electronic parameters (e.g., shaping time) and predicts detector test conditions such as operating voltage and gas composition. A half-sized CEE-MWDC prototype demonstrated anode-wire position accuracy with standard deviation less than 20 µm. This prototype utilized practical designs to verify feasibility for large-scale engineering development. The detector measured the ^{55}Fe source energy spectrum using commercial electronics; the energy spectrum near the window was distorted, but a proposed solution significantly improved the spectrum, achieving 19.7% energy resolution. Joint testing with self-developed integrated FEE, SCA waveform sampling, and acquisition system achieved 22% energy resolution for 5.9-keV X-rays and 330 μm track residuals for cosmic rays. Both energy and position resolution performance meet CEE requirements.

Author Contributions: All authors contributed to the conception and design of this study. Material preparation, data collection, and analysis were performed by all authors. The first draft was written by Zhoubo He and Zhi Qin. Limin Duan, Zhigang Xiao, and Rongjiang Hu commented on and revised previous versions. All authors have read and approved the final manuscript.

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