Beam test results of the prototype of the multi wire drift chamber for the CSR external-target experiment

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Abstract

The half-size prototype of the multi wire drift chamber (MWDC) for the cooling storage ring (CSR) external-target experiment (CEE) was assembled and tested in 350 MeV/u Kr+Fe reactions on the heavy ion research facility in Lanzhou (HIRFL). The prototype consists of 6 sense layers, where the sense wires are stretched in three directions X, U and V, meeting 0°, 30° and -30° with respect to the vertical axis, respectively. The sensitive area of the prototype is 76cm $\times$ 76cm. The amplified and shaped signals from the anode wires are digitized in a serial capacity array. Being operated with 1500 V high voltage on the anode wires, the efficiency for each layer is beyond 95%. The tracking residual is about 301 ± 2 m. The performance meets the requirements of CEE.

Full Text

Preamble

Beam Test Results of the Multi-Wire Drift Chamber Prototype for the CSR External-Target Experiment

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A half-size prototype of the multi-wire drift chamber (MWDC) for the cooling storage ring (CSR) external-target experiment (CEE) was assembled and tested in 350 MeV/u Kr+Fe reactions at the Heavy-Ion Research Facility in Lanzhou (HIRFL). The prototype consists of six sense layers, with sense wires stretched in three directions (X, U, and V) oriented at 0°, 30°, and -30° relative to the vertical axis, respectively. The sensitive area of the prototype is 76 cm × 76 cm. Signals from the anode wires were amplified, shaped, and digitized using a serial capacity array. At an operating voltage of 1500 V on the anode wires, each layer achieved an efficiency greater than 95%, with a tracking residual of approximately 301 ± 2 μm. This performance meets the requirements of CEE.

Keywords: Multi-wire drift chamber (MWDC), CSR external-target experiment (CEE), tracking

INTRODUCTION

Heavy-ion collisions (HICs) in the beam energy region from hundreds of MeV/u to a few GeV/u create nuclear matter at densities a few times the saturation density \cite{1–6}. Consequently, researchers can investigate the nuclear matter equation of state (nEOS), collision dynamics, and QCD phase structure through observables extracted from HICs, including directed flow, elliptic flow, triangular flow, meson production, and correlation functions \cite{7–13}. Thanks to the operation of various experimental facilities—including KAOS, FOPI, HADES, and SπRIT, to name a few—significant progress has been made in constraining the nEOS over recent decades \cite{14–19}.

The most uncertain aspect of the nEOS thus far is the isovector sector, namely the density dependence of the nuclear symmetry energy $E_{\text{sym}}(\rho)$, particularly above ρ_0, where ρ_0 is the saturation density. Substantial progress has been made in the last decade in constraining the density behavior of $E_{\text{sym}}(\rho)$ near ρ_0 by comparing various experimental probes—including π^-/π^+ yield ratios and neutron-to-proton differential flow—with transport model predictions \cite{20–25}. Despite this progress, the complicated production and transport features of mesons and light nuclei in HICs mean that studies on precise HIC modeling and extraction of $E_{\text{sym}}(\rho)$ are still ongoing, as part of the Transport Model Evaluation Project (TMEP) \cite{26–28}. Experimental efforts continue, and by combining observations of the gravitational wave event GW170817 from neutron star mergers [**?**, **?**] with nuclear physics data from terrestrial laboratories, constraints are becoming more convergent \cite{31–33}. However, significant uncertainties remain, and several questions are still unanswered, such as the convolution of clustering and transport of the isospin degree of freedom [?, ?], along with inconsistencies between the neutron skin thicknesses of ^{208}Pb and ^{48}Ca \cite{36–40}. The constraint on $E_{\mathrm{sym}}(\rho)$ has become unprecedentedly important since the GW170817 observation; for recent reviews, see Refs. \cite{41–43}.

Due to the long-standing interest and significance of nEOS studies, several new facilities providing heavy-ion beams from several hundred MeV/u to a few GeV/u have been constructed or proposed worldwide, such as CBM at FAIR, MPD at NICA, and LAMPS at RAON \cite{44–46}. The Cooling Storage Ring (CSR) at the Heavy-Ion Facility in Lanzhou (HIRFL) is an accelerator complex that provides beams of all stable ion species with maximum energies of 2.8 GeV/u for protons and 0.5 GeV/u for uranium [?]. When equipped with an advanced experimental device, HIRFL-CSR can provide novel opportunities for studying various topics, including the properties of nuclear matter. For instance, one can revisit the π^-/π^+ yield ratio and $t/^3$He production in HICs at beam energies of hundreds of MeV/u [?, ?]. Additionally, using proton-induced collisions on heavy targets at 2.8 GeV incident energy, strangeness baryons such as Λ can be created, enabling investigation of p-Λ interactions in cold nuclear matter at normal density via correlation functions, which have been widely applied to study the spatiotemporal distribution of collisions and particle interactions \cite{49–52}.

After a decade of research and development, the CSR External-Target Experiment (CEE) is currently under construction \cite{53–55}. It can measure light charged particles (LCPs) over nearly the entire 4π solid angle in the center-of-mass frame. [Figure 1: see original paper] shows a schematic view of the CEE experiment. The main component is a large-gap magnetic dipole that houses the tracking detectors. For mid-rapidity, LCPs are tracked using two time projection chambers (TPCs) placed side-by-side, with an empty space in the middle for the beam to pass through. An inner time-of-flight (iTOF) wall is mounted on the left, right, and bottom sides of the TPCs to measure TOF information for mid-rapidity tracks. For the large-rapidity region, an array consisting of three multi-wire drift chambers (MWDCs) followed by an external TOF wall (eTOF) is designed to measure LCPs. Both eTOF and iTOF are made of multi-layer resistive plate counters (MRPC), requiring time resolutions of approximately 60 ps and 50 ps, respectively. A zero-degree counter (ZDC) is mounted downstream to determine the reaction plane and provide complementary information for centrality determination. Other sub-detectors, including the start-time detector T0, active collimator (AC), and silicon pixel beam spot monitor (BM), are mounted upstream of the target on the beam line. According to the CEE conceptual design, the MWDC array must achieve a tracking residual of 300 µm and a momentum resolution of 5%. The maximum event rate is 10^4 Hz, corresponding to a beam intensity of 10^6 pps when using a 1% interaction target [?].

Since the start of the CEE project, extensive R&D has been conducted, and all sub-detectors have progressed beyond the design stage. Currently, all CEE prototypes have been tested using cosmic rays and ion beams and have entered the engineering verification phase \cite{48,57–66}. For the MWDC in particular, design, manufacturing, assembly, and source tests are detailed in Ref. [**?**]. In this study, we focus on the beam test results of the MWDC prototype and demonstrate that its performance satisfies CEE requirements.

II. EXPERIMENTAL SETUP OF THE BEAM TEST

The beam test experiment was performed at the CEE site in HIRFL-CSR. A 350 MeV/u Kr beam was delivered by the CSR main ring, striking an iron target approximately 1 mm thick. [Figure 2: see original paper] shows a schematic view (a) and a photograph (b) of the detector setup in the beam test. The sub-detector prototypes were installed at approximately 20° relative to the beam direction. Behind the target is the start-timing detector T0, followed by two iTOF MRPCs (iTOF1 and iTOF2) and two eTOF MRPCs (eTOF1 and eTOF2). Further downstream is a full-sized TPC prototype. The MWDC, sandwiched between two scintillators SC1 and SC2, was placed approximately 20 cm behind the TPC. At the farthest downstream position is the ZDC prototype.

The half-sized MWDC prototype had the same structure as the final MWDC to be installed in CEE, though with a smaller sensitive area of 76 cm × 76 cm. The prototype consists of six sense wire layers stretched in three directions (X, U, and V), meeting angles of 0°, 30°, and -30° relative to the vertical axis, as shown in Figure 3: see original paper. Each drift cell measures 10 mm × 10 mm, with an inter-sense-wire distance of 10 mm. Figure 3: see original paper schematically shows the wire distributions for two neighboring drift cells in the X sense plane, viewed in transverse cross-section. In each direction, the two parallel sense planes are displaced by half a cell to resolve left-right ambiguity when a track passes through. The high voltage (HV) applied to the sense wires was 1500 V, and the working gas was a mixture of 80% argon and 20% CO_2 at slightly above atmospheric pressure. Under these conditions, the energy resolution is about 22% for 5.9 keV X-rays in ^{55}Fe source tests [**?**].

Owing to the large area of the MWDC in CEE, maintaining wire distance rigidity and precision requires a very thick and wide frame using conventional manufacturing techniques. However, since the MWDC is placed in a dipole magnet with limited space, the dead area caused by the frame must be minimized. Therefore, a new technique was developed to fabricate the wire plane. Wires pre-stretched on a rigid aluminum alloy frame with carbon fibers were transferred to separate PCB boards attached to various duralumin ladders, which were mounted on the entire duralumin support frame. Each PCB covers only a partial area of the wires in each plane. Accurate wire spacing is further maintained by applying a fine-machined sawtooth structure, achieving wire spacing precision better than 20 µm. For hardware manufacturing details, refer to Ref. [**?**].

Signals from the sense wires are amplified and shaped by front-end electronics (FEE) mounted on PCB boards, with each board housing 32 channels. The FEE signals are then sent to a serial capacity array (SCA) for digitization \cite{67–69}, where pulses are sampled at 80 MHz followed by analog-to-digital conversion. Each SCA board houses 16 channels, and six SCA boards are grouped into one back-end data module (BDM), which reads data from the SCA and sends it to the main data acquisition (DAQ) system upon receiving a global trigger signal. In the beam test, 192 channels of the MWDC prototype were connected, corresponding to 32 readout wires on each sense wire plane. [Figure 4: see original paper] shows the electronics scheme and signal flow for the MWDC prototype.

The trigger system was built using field-programmable gate array (FPGA) technology. Signals from the iTOF and eTOF detectors were collected by FEE boards to calculate multiplicity, which was fed into the main trigger module (MTM) via optical fiber connections. When the trigger condition was satisfied, the MTM generated a trigger signal and sent it to all sub-detectors via downlink chains. In the beam test, our trigger condition required coincidence of T0, iTOF, and eTOF. For detailed construction of the FPGA-based trigger system, refer to Ref. [**?**].

III. RESULTS AND DISCUSSIONS

This section presents the performance of the MWDC prototype in the beam test experiment.

[Figure 5: see original paper] shows a typical event display where six wires were fired by an incident particle. The last two panels with green fits show signals from scintillators SC1 and SC2. The abscissa represents sampling time in ns, with a bin width of 12.5 ns due to the 80 MHz sampling rate. The ordinate indicates signal amplitude. The signal shape is smooth, with a rise time of 100 ns and a fall time of 200 ns. The baseline is stable in each channel, with fluctuations of approximately 25 channels, corresponding to 8 mV based on our calibration.

Once a signal is identified in an individual channel, an asymmetric Gaussian function is used to fit the signal, with amplitude as a direct fitting parameter. Figure 6: see original paper shows the distribution of signal amplitudes from fired wires. As expected, the distribution follows an approximate Landau shape. The most probable amplitude is approximately 200 channels, corresponding to about 70 mV. Assuming incident particles are primarily protons with an average kinetic energy of 200 MeV, the most probable energy loss is estimated to be approximately 5.4 keV. The energy deposit of minimum ionization particles averages 2 keV and is expected to be around 25 mV, which exceeds the baseline fluctuation.

The asymmetric Gaussian function provides the rising and falling edges of the signal waveform, and timing information is extracted using a constant-fraction discriminator algorithm with a fraction of 0.1. The times of the two scintillators recorded by the SCA are obtained using the same algorithm with a fraction of 0.5. Drift time is derived from the time difference between wire and scintillator signals, accounting for variations in the start time of the self-trigger sampling window across different SCA boards. Figure 6: see original paper shows the drift time distribution for fired wires relative to the timing provided by SC1 and SC2. Besides the main peak with a width of approximately 100 ns, there is a long tail corresponding to signals originating from the corners of drift cells. The main peak rises rapidly, indicating good zero-drift time determination.

The histogram in Figure 7: see original paper shows the count distribution across all six layers for events triggered by coincidence of scintillators SC1 and SC2. Layers 2 and 5 show slightly lower counts because each had one dead channel. The efficiency of the six layers is represented by solid dots on the right ordinate. Efficiency was 95% for layers 2 and 5 and 98% for the others. The efficiency of each individual layer is derived by counting firing (0 or 1) on wires near the track crossing point, which is recognized in the remaining five layers. Panel (b) shows the multiplicity distribution of fired layers. Clearly, most events fire an even number of layers, as expected because fired wires in a given direction (X, U, and V) typically come in pairs. Since the coverage of connected wires is slightly smaller than the area of scintillators in front of and behind the MWDC prototype, some tracks registered by the scintillators miss the connected wires, causing the multiplicity distribution to partially peak at 2 and 4.

Before demonstrating the tracking performance of the MWDC prototype, we investigated the R-T calibration, where R and T are drift distance and drift time, respectively. Calibration was performed using an iterative scheme. The curve calculated from Garfield++ code [**?**] was adopted as the initial R-T curve, shown as the dashed curve in [Figure 8: see original paper]. With this initial condition, tracks were fitted and tracking residuals were calculated as a function of drift distance R. Once obtained, the tracking residual was used to correct the drift distance and the fit was repeated. After several iterations, the R-T curve converged. The solid curve represents the calibrated R-T curve, showing a drift velocity in the middle of the drift cell of approximately $v_d \approx 4.5$ cm/µs. The color palette shows the R-T event distribution. The width of this distribution contains information on the tracking residual δR, defined as the difference between the measured drift distance R obtained from drift time and the R-T curve and the expected drift distance R_{exp} after tracking: $\delta R = R - R_{\text{exp}}$, as depicted in the inset of [Figure 8: see original paper].

Figure 9: see original paper shows the tracking residual distribution, counting only tracks that fired all six sense wire layers. The distribution exhibits a Gaussian shape. Using a Gaussian fit, the residual was determined to be $\sigma_t = 301 \pm 2$ µm. This result is consistent with our previous test of a 10 cm × 10 cm prototype using cosmic-ray muons [**?**], suggesting that tracking performance did not deteriorate with increased sensitive area. The tracking residual meets the expected performance of the CEE MWDC array, which is 300 µm in the design

[?]. Defining the beam direction as the Z-axis and the vertical direction as the Y-axis in the laboratory, the azimuthal angle ϕ and polar angle θ distributions for tracks measured by the MWDC prototype are shown in panels (b) and (c), respectively. The peaks of θ and ϕ are situated at $\langle\theta\rangle = 20°$ and $\langle\phi\rangle = 180°$, indicating that tracks originate from the target position as expected.

The final problem to be solved for MWDC application in CEE is that in real beam experiments, the majority of unreacted beam particles pass through the MWDC array, causing serious saturation problems for the entire system. To address malfunctions arising from unreacted beam particles, we designed a deactivated area for each MWDC. [Figure 10: see original paper] shows an engineering prototype of the MWDC recently assembled with the same size as the real MWDC1 to be installed in CEE. A stack of hollow rectangular PCBs, each corresponding to a wire frame layer, was mounted at the MWDC center. Wires near the beam line are soldered to the PCB as a bridge circumventing the beam path rather than passing through the entire area. The deactivated area measures approximately 30 cm (x) $\times$ 10 cm (y) for the nearest MWDC (MWDC1) and 60 cm (x) $\times$ 20 cm (y) for the farthest MWDC (MWDC3) relative to the target. To verify this design, we performed a new beam test with the engineering prototype placed on a beamline. At a beam intensity of 2×10^6 pps—higher than typical future experimental conditions—the rate of large-amplitude signals on the MWDC was much less than 10^{-3} of the beam intensity. These low-rate signals, mainly induced by projectile-like products from beam interactions with upstream materials, cause no operational problems. Simulation-based transport models and Geant4 packages suggest that introducing the deactivated area causes insignificant loss of production, as inefficiency only appears below 3° in the laboratory [?].

We also verified that the deactivated area did not influence the energy resolution of the prototype detector. As an example, [Figure 11: see original paper] shows the X-ray energy spectra from a ^{55}Fe source recorded in two neighboring wires from the engineering prototype, using the same electronic setup as in [Figure 4: see original paper]. The results show an energy resolution of approximately 22%, consistent with a prototype without a deactivated area [?]. The tracking performance of the CEE MWDC prototype is comparable to the CLAS experiment, which reported a resolution of 310–395 µm for the middle portion of the cell [?], and to the MWDC of the same type operated at the ETF on RIBLL-II, which achieved 230 µm spatial resolution for 311 MeV/u ^{40}Ar beam particles [?]. The beam and source test results demonstrate that the MWDC prototype, together with its electronics, can meet the requirements of the CEE experiment.

IV. CONCLUSION

In conclusion, a prototype of the MWDC detector for CEE was assembled and operated in a beam test experiment with 350 MeV/u Kr+Fe collisions. The MWDC prototype and all other detectors, trigger systems, and DAQ systems were integrated in the beam test. At a working voltage of 1500 V, the MWDC operated correctly with an average efficiency exceeding 95% for all sense wire layers. The baseline fluctuation is approximately 7 mV. The R-T curve was calibrated, yielding a drift velocity of $v_d \approx 4.5$ cm/µs. For events with $M_{\text{layer}} = 6$, the tracking residual is approximately 301 ± 2 µm. The energy resolution of the engineering prototype is typically 22% for ^{55}Fe X-rays, unaffected by the introduction of a deactivated central area to avoid malfunctions caused by unreacted beam particles. These experimental results demonstrate that the MWDC satisfies the requirements of the CEE experiment.

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