

## Construction and performance test of the drift chambers at the target area of the External Target Facility of CSR

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### Abstract

The multiwire drift chambers at the target area of the External Target Facility of CSR are constructed for tracking radioactive ion beams that enter and exit the target. Two drift chambers with a sensitive area of  $8 \times 8$  cm<sup>2</sup> are positioned upstream of the target, while another two drift chambers with a sensitive area of  $16 \times 16$  cm<sup>2</sup> are placed upstream of the target. The drift chambers were tested using 350 MeV/u <sup>78</sup>Kr beams and cocktail secondary beams. To improve drift time precision, the time walk effect is corrected by using the measured energy. The impact of  $\delta$ -rays on the multiplicity and spatial resolution is assessed using beams with various atomic number and different applied voltages. The optimal voltage to minimize the impact of  $\delta$ -rays is obtained. An optimal spatial resolution of 35  $\mu$ m for the drift chambers is achieved.

### Full Text

### Preamble

#### Construction and Performance Test of the Drift Chambers at the Target Area of the External Target Facility of CSR

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The multiwire drift chambers at the target area of the External Target Facility of CSR are constructed for tracking radioactive ion beams that enter and exit the target. Two drift chambers with a sensitive area of  $80 \text{ mm} \times 80 \text{ mm}$  are positioned upstream of the target, whereas another two drift chambers with a sensitive area of  $160 \text{ mm} \times 160 \text{ mm}$  are placed downstream of the target. The drift chambers were tested using  $350 \text{ MeV/u } ^{78}\text{Kr}$  beams and cocktail secondary beams. To improve drift time precision, the time walk effect is corrected using the measured energy. The impact of  $\delta$ -rays on the multiplicity and spatial resolution is assessed using beams with various atomic numbers and different applied voltages. The optimal voltage to minimize the impact of  $\delta$ -rays is obtained. An optimal spatial resolution of  $35 \text{ }\mu\text{m}$  for the drift chambers is achieved for heavy nuclei.

**Keywords:** drift chamber, track reconstruction, spatial resolution, radioactive ion beam,  $\delta$ -ray

## Introduction

Multiwire drift chambers are widely used in nuclear physics experiments to track charged particles. They have high detection efficiencies and can measure the position of ions with good spatial resolution, typically around a few hundred  $\mu\text{m}$  or even better [1, 2]. Drift chambers have been broadly employed in large-acceptance spectrometers for radioactive ion beam physics experiments, such as SAMURAI [3] at the RIKEN RI Beam Factory (RIBF), S800 [4] at the National Superconducting Cyclotron Laboratory (NSCL), and the External Target Facility (ETF) [5-8] at the Heavy Ion Research Facility in Lanzhou-Cooler Storage Ring (HIRFL-CSR) [9-11].

The ETF is designed for studies on nuclear structure and reactions involving radioactive ion beams (RIBs) that are produced by the second Radioactive Ion Beam Line in Lanzhou (RIBLL2) [12-14]. A schematic illustration of the setups at the ETF target area is shown in Fig. 1 [Figure 1: see original paper]. At the ETF target area, two sets of target-front drift chambers (FDCs) and two sets of target-rear drift chambers (RDCs) are developed. Their purpose is to reconstruct the tracks of particles before and after they cross the reaction target. Two multiple sampling ionization chambers, named MUSIC1 and MUSIC2 [15, 16], are positioned before and after the target, respectively, to measure the energy loss ( $\Delta E$ ) of incident and outgoing particles. A plastic scintillator is installed in front of FDC1 to measure beam arrival time. Particle identification

at the ETF is achieved through the B -TOF- $\Delta E$  method [17]. The B is obtained from track reconstruction, which is based on the positions and angles of particles measured by the tracking detectors upstream and downstream of the large gap magnet (not shown in Fig. 1). Therefore, the spatial resolution of drift chambers is crucial for precise particle identification [18, 19].

This paper offers a comprehensive description of the construction of the target area drift chambers and highlights the results from beam tests. Section 2 delves into the design details of both the FDCs and RDCs. Section 3 describes the conditions of the beam tests. In Section 4, we focus on the determination of drift time, with a particular emphasis on the method developed to correct for the time walk effect. Section 5 explores the influence of  $\delta$ -rays under varying applied voltages and beam atomic numbers. The discussion in Section 6 centers on multiplicity of drift chambers, examining how different voltages and atomic numbers affect the performance. Section 7 outlines the method used to derive the space-time (r-t) relation. Finally, Section 8 presents the track fitting method, investigates the spatial resolution under various conditions, and provides the optimal spatial resolution achievable in the drift chamber at the optimal voltage.

## II. Design of the Drift Chambers

Two FDCs are identical and have a sensitive area of  $80 \text{ mm} \times 80 \text{ mm}$ . Similarly, the two RDCs are also identical and have a sensitive area of  $160 \text{ mm} \times 160 \text{ mm}$ . The downstream RDCs are designed to be larger in size than the upstream FDCs, since the reaction products may exit at a large angle. Although both types of drift chambers differ in size, they share the same structure.

Each FDC (RDC) consists of two sub-drift chambers, which are responsible for measuring positions in the x and y directions, respectively (see Fig. 2 [Figure 2: see original paper]). The wires in the two sub-drift chambers are arranged perpendicular to each other. Except for the wire orientations, all other parameters of the two sub-drift chambers are identical. Each sub-drift chamber contains five layers of wires, with two layers of sense wires and three layers of cathode wires arranged alternately. The four sense wire layers are aligned along the beam direction in the order of X1, X2, Y1 and Y2. The spacing between the X1 and X2 layers in the FDCs (RDCs) is 5 mm (10 mm), and the same is true of the Y1 and Y2 layers. Furthermore, the distance between each sense wire layer and its adjacent cathode wire layers is 2.5 mm (5 mm). The sense wires in the FDCs (RDCs) are 20  $\mu\text{m}$  gold-plated tungsten wires, while the cathode wires are 75  $\mu\text{m}$  (100  $\mu\text{m}$ ) copper-tungsten alloy wires.

In FDCs (RDCs), the sense wires and field wires (using the same wires as the cathode wires) are alternately arranged with a spacing of 2.5 mm (5 mm) between the wires (see Fig. 2) to ensure a uniform electric field within each cell. Accordingly, the area of each drift cell is  $5 \text{ mm} \times 5 \text{ mm}$  ( $10 \text{ mm} \times 10 \text{ mm}$ ) for FDCs (RDCs). Furthermore, the X1 layer and X2 layer are offset by 2.5 mm (5 mm) to address the left-right ambiguity in the drift chambers, with the same

offset applied to the Y1 layer and the Y2 layer.

The working gas used in the drift chambers is a mixture of 80% argon and 20% carbon dioxide at room temperature and atmospheric pressure in the gas flow mode. The drift chamber windows, made of 25  $\mu\text{m}$  thick aluminum-plated Kapton film, serve to separate the ambient air from the working gas. During operation, a positive voltage is applied to the sense wires, while the cathode wires are kept grounded. The specifications of the FDCs (RDCs) are provided in Table 1, and Fig. 3 shows an internal photograph of the actual drift chamber.

Each layer of sense wires in the FDCs (RDCs) outputs signals to 16 readout channels, totaling 64 channels per chamber. The readout signals from the sense wires are amplified and discriminated by the charge-sensitive amplifier shaper discriminator SFE16 [20] chips. The time digitization is achieved using the high-performance time-to-digital converter (HPTDC) [21], which records the leading and trailing edge times of the signals in high-resolution mode, offering a resolution of 100 ps [22]. The electron drift time in the drift chambers is on the order of 0.1  $\mu\text{s}$ , whereas positive ions drift three orders of magnitude more slowly, taking approximately 100  $\mu\text{s}$ . To prevent the accumulation of positive ion signals, the drift chambers are operated at rates below  $10^4$  pps.

### III. Experimental Test Conditions

The performance of the drift chambers was evaluated in a test experiment using 350 MeV/u  $^{78}\text{Kr}$  primary beams and a series of secondary beams with the atomic number  $Z$  from 20 to 36 produced by the fragmentation of  $^{78}\text{Kr}$  ions. The particle identification spectrum of the secondary beams delivered by RIBLL2 and used in this test is presented in Fig. 4 [Figure 4: see original paper]. In order to ascertain the impact of voltage on the performance of the drift chamber, a series of voltages were applied during the test. The voltage settings used for the primary beam tests were  $U = 650$  V, 700 V, 750 V and 800 V. In the secondary beam test, the voltage settings were  $U = 650$  V, 750 V, 850 V, and 900 V.

### IV. Drift Time and Correction for Time Walk

The drift time is obtained by subtracting the time measured by the plastic scintillator from the time recorded by the drift chambers. Because beams with different atomic numbers deposit different amounts of energy  $\Delta E$  in the drift chambers, and the time measured by the drift chambers is determined using the leading edge discrimination method, a significant time walk effect occurs for beams with large charge differences. Particles with larger  $\Delta E$  in the drift chambers exhibit steeper signal leading edges, resulting in shorter measured drift time. To ensure that particles with different  $\Delta E$  can use the same  $r$ - $t$  relation under identical conditions, the time walk correction is necessary.

The energy loss of the particles in the FDCs (RDCs) is correlated with the energy loss  $\Delta E$  measured by MUSIC1 (MUSIC2) placed upstream (downstream) of the

target (see Fig. 1). As an example, the relation between drift time and  $\Delta E$  for the FDC in the secondary beam test at a voltage of 900 V is shown in Fig. 5(a) [Figure 5: see original paper]. The starting points in the drift time spectra for different isotopes should coincide at 0 ns. However, because of the time-walk effect, the drift time starting points for the particles exhibit a curved relation with  $\Delta E$ , as shown in Fig. 5(a).

The correlation between  $\Delta E$  and the starting points of drift time is fitted using a square root function, which is selected empirically:  $\Delta t = a/\sqrt{\Delta E} + b + c$ . Then the corrected drift time can be obtained by  $t = t_0 - \Delta t$ , where  $t_0$  is the original drift time. After the correction for the time walk, the drift time starting points are independent of  $\Delta E$ , as can be seen in Fig. 5(b). Moreover, the leading edge of the drift time spectrum becomes steeper after correction, as demonstrated in Fig. 6 [Figure 6: see original paper].

## V. Impact of $\delta$ -Rays

When heavy ions pass through the drift chamber, high-energy  $\delta$ -rays may be generated [23, 24]. If the voltage is too high,  $\delta$ -ray signals may be acquired simultaneously with the beam signals and bias the drift time measurement. We used different beams and applied various voltages to systematically investigate the impact of  $\delta$ -rays on the drift time. The best voltage condition to reduce the  $\delta$ -ray effect for each kind of beam was evaluated.

Fig. 7 [Figure 7: see original paper] shows the relation between the drift time ( $t_1$ ) measured by X1 layer and that ( $t_2$ ) by X2 layer in the FDC under different conditions: (a)  $U = 650$  V and  $Z = 36$ ; (b)  $U = 900$  V and  $Z = 36$ ; (c)  $U = 900$  V and  $Z = 20$ . Since the incident beam is generally perpendicular to the detector, if the particle's incident position is close to the sense wire in one layer, it will consequently be farther from the sense wire in another layer. As a result, the  $t_1$ - $t_2$  distribution for two adjacent sense wires in different layers should ideally form a crescent-shaped curve as shown in Fig. 7(a) and (c), where proper voltages were applied.

If the drift time is affected by  $\delta$ -rays, distortions will appear in the  $t_1$ - $t_2$  plot. Specifically, if  $\delta$ -rays travel closer to the fired sense wire than the heavy ions, the  $\delta$ -rays will cause earlier signals and shorten the drift time. This feature can be seen in the lower part of the curve in Fig. 7(b) when a higher voltage is applied. On the other hand,  $\delta$ -rays may also activate sense wires not traversed by the heavy ions and produce false signals with a larger drift time, clearly visible in the upper right of the curves in Fig. 7(b). Given the low charge of  $\delta$ -rays, the number of primary ionized electrons they produce in the drift chamber is limited. At lower voltages, the primary electrons are more prone to recombination with the gas, which hinders the generation of signals from  $\delta$ -rays on the sense wire. In contrast, at higher voltages,  $\delta$ -rays more readily produce signals, resulting in a greater impact. Consequently, the distortion of the  $t_1$ - $t_2$  distribution observed in Fig. 7(b) is greater than that in Fig. 7(a). Since particles with larger  $Z$  are

more likely to emit  $\delta$ -rays as they pass through the drift chamber, the distortion is more pronounced for  $Z = 36$  compared to  $Z = 20$  at the same voltage.

## VI. Multiplicity

The multiplicity ( $M$ ) distributions for the fired sense wires in a layer are investigated. Fig. 8 [Figure 8: see original paper] shows the proportion of  $M$  as functions of  $Z$  and  $U$  for the FDC. Here,  $M = 0$  indicates that the wire layer was unable to detect the particle as it entered the chamber. In contrast,  $M > 1$  suggests that a single incident particle has generated multiple signals in the wire layer, mainly caused by erroneous signals from  $\delta$ -rays. The impact of  $\delta$ -rays on the drift chamber is weak when  $P(M = 1)$ , defined as the proportion of events with  $M = 1$ , is high.

Fig. 8(a) shows  $P(M = 1)$  and  $P(M \geq 1)$  as functions of voltage for the FDC at  $Z = 36$ . When the voltage is low, a moderate increase enhances the drift chamber's detection efficiency. However, once the voltage exceeds a certain threshold (750 V), the influence of  $\delta$ -rays becomes more pronounced, causing a significant decrease in  $P(M = 1)$ . Fig. 8(b) illustrates  $P(M = 1)$  and  $P(M \geq 1)$  as functions of the incident beam atomic number  $Z$  for the FDC at  $U = 900$  V. It can be seen that  $P(M = 1)$  decreases as  $Z$  increases at such a high voltage. This is because an increase in  $Z$  results in a higher emission of  $\delta$ -rays by the beams in the gas [25, 26]. This increase in  $\delta$ -rays leads to a rise in  $P(M > 1)$  and a reduction in  $P(M = 1)$ .

## VII. The r-t Relation

The drift distance-drift time ( $r$ - $t$ ) relation enables the calculation of the distance from the initial ionization position to the sense wire, thus allowing the position of the particle to be determined. The  $r$ - $t$  relation varies under different conditions, resulting from the significant dependence of the electron drift velocity in the drift chamber on factors such as the working gas and voltage. Consequently, distinct  $r$ - $t$  relations need to be employed for various scenarios.

A commonly used method for parameterizing the  $r$ - $t$  relation involves simulating an initial  $r$ - $t$  relation and iteratively refining it through polynomial fitting [27, 28]. However, the function obtained through this iterative method struggles to capture the irregularities caused by the non-uniform electric field at the edges of the drift chamber. Another method for obtaining the  $r$ - $t$  relation is through integrating the drift time spectrum [25]. Under the condition of uniformly incident particles, this method better captures the irregularities of the electric field within the drift chamber.

In the present experiment, the beam spot covers multiple drift cells. For the entire drift chamber, the distance  $r$  from the particles to the sense wire can be approximately considered to be uniformly distributed. Therefore, the method of integrating the drift time spectrum is adopted to obtain the  $r$ - $t$  relations.

Assuming that the probability density function of the drift time spectrum is represented by  $f(t)$ , and the probability density function of drift distance is  $g(r)$ , the relationship between  $g(r)$  and  $f(t)$  can be expressed as  $g(r)dr = f(t)dt$ , and the drift velocity  $v(t)$  can be obtained from the formula  $v(t) = f(t)/g(r)$ . If the drift distance is uniformly distributed, then  $g(r) = 1/d$ , where  $d$  represents the maximum drift distance of primary electrons. Thus,  $v(t)$  can be expressed as  $v(t) = f(t)d$ . Consequently, the r-t relation function,  $r(t)$ , can be obtained as  $r(t) = \int_0^t v(\tau)d\tau = d \int_0^t f(\tau)d\tau$ .

The upper limit of the r-t relation is  $d$ , and its value is related to the proportion of events with  $M \geq 1$  ( $P(M \geq 1)$ ). Events in which the distance between the primary electrons and the sense wires exceeds  $d$  cannot generate signals ( $M = 0$ ), resulting in a loss of  $P(M \geq 1)$ . Therefore,  $d$  can be expressed as  $d = L \cdot P(M \geq 1)$ , where  $L$  represents the length of the drift cell. For FDC (RDC),  $L = 2.5$  mm (5 mm). The detection efficiency, represented by  $P(M \geq 1)$  (see Fig. 8), varies under different conditions, and  $d$  changes accordingly.

Fig. 9 [Figure 9: see original paper] shows the r-t relation of FDC derived from the integrated drift time spectrum method under two different applied voltages:  $U = 750$  V and  $U = 650$  V. The  $P(M \geq 1)$  values at 750 V and 650 V are 98.9% and 92.8% (see Fig. 8(b)), with the corresponding upper limits  $d = 2.47$  mm and 2.32 mm, respectively.

The quality of the obtained r-t relation can be evaluated based on the correlation between the two drift distances,  $r_1$  and  $r_2$ , deduced from two adjacent layers. For particles incident perpendicular to the sense wire plane, the relation  $r_1 + r_2 = 2.5$  mm (5 mm) for the FDC (RDC) should be satisfied, as illustrated in Fig. 10(a) [Figure 10: see original paper]. The scatter plot of  $r_1$  and  $r_2$  for the FDC, obtained from the beam test, is presented in Fig. 10(b). It can be seen that the  $r_1$ - $r_2$  relation shows a linear trend consistent with the  $r_1 + r_2 = 2.5$  mm relation (red line), indicating the accuracy of the r-t relation. A slight broadening in the  $r_1$ - $r_2$  distribution is observed, which is attributed to the divergence of the beam angle and the uncertainty in drift time. Fig. 10(c) shows the projection of Fig. 10(b) onto the line  $y = x$ , exhibiting a Gaussian distribution with a mean of 2.496 mm.

## VIII. Beam Tracking and Spatial Resolution

In nuclear physics experiments, the reconstruction of ion trajectories plays an important role in high-precision position and momentum measurements [29, 30], as well as in the identification of charged particles. In the ETF target area, particle tracks are divided into two sections: before and after the target. The FDCs and RDCs are employed to reconstruct the tracks in each section.

The track fitting is performed using signals from the four sense wire layers in the two FDCs (RDCs), with a requirement for signals from at least three layers. Initially, the hit positions are assumed to be at the positions of the fired sense wires, labeled as  $W_1$ - $W_4$  for the four layers in Fig. 11(a) [Figure 11: see original

paper]. The initial track is obtained by fitting the assumed hit positions using the least squares method. The updated hit positions, denoted as  $P_1$ - $P_4$ , are then calculated using the initial track information and the drift distance  $r$  derived from the  $r$ - $t$  relation of the  $i$ -th layer, as depicted in Fig. 11(a). An updated track is subsequently obtained by fitting the updated hit positions. This process of updating  $P_1$ - $P_4$  and the track will be performed iteratively.

The distance from the track to the fired sense wire of the  $i$ -th layer is denoted as  $r_i$ . And the residual is defined as the difference between  $r_i$  and  $r$ , which can be expressed as  $\Delta r_i = r_i - r$ . Then the sum of squared residuals is expressed as  $\Sigma(\Delta r_i)^2$ . The track iteration process is repeated multiple times until the sum of the squared residuals reaches its minimum. This fitting process essentially works like finding the common tangent to the circles centered at  $W_1$ - $W_4$  with  $r_i$  as their radii [31].

The scattered points in Fig. 11(b) represent  $r$ - $t$  relation in RDC, with the employed  $r$ - $t$  relation superimposed. The degree of conformity between the scattered points and  $r$ - $t$  relation reflects the quality of the fitted tracks. The majority of the scattered points generated by the fitted tracks form a band that aligns well with the  $r$ - $t$  relation. It can be observed that, at drift distances greater than 4.5 mm, the electron drift time becomes significantly prolonged due to the weak electric field and the meandering of the field lines [32].

The meandering of field lines at the edges of the drift cell can be effectively illustrated by the difference in spatial resolution between the edges and the interior of the drift cell. The spatial resolution of the drift chamber can be characterized by the standard deviation ( $\sigma$ ) of the residual ( $\Delta$ ) distribution [33-35]. Fig. 12 [Figure 12: see original paper] illustrates the variation of spatial resolution with electron drift distance. It is evident that in the region where the drift distance exceeds 4.5 mm, the spatial resolution significantly deteriorates. Similarly, the position resolution is also relatively poor at drift distances below 0.5 mm. This is because, during track fitting, the drift distance on another sense wire layer in the drift chamber exceeds 4.5 mm, leading to an overall degradation in position resolution. Additionally, a noticeable decline in spatial resolution is observed at a drift distance of approximately 2.5 mm, which is attributed to particles hitting the cathode wires of the drift chamber (as shown in Fig. 10(a)).

We also investigated the variation in the overall spatial resolution of the drift chamber under different test conditions to assess the impact of  $\delta$ -rays on spatial resolution. Fig. 13 [Figure 13: see original paper] shows the spatial resolution as functions of  $Z$  and  $U$  for the RDC. At a low voltage,  $\delta$ -rays are unlikely to generate signals in the drift chamber, and particles with higher  $Z$  achieve better spatial resolution [36]. However, at excessively high voltage, the influence of  $\delta$ -rays increases, resulting in a rapid deterioration of spatial resolution. This feature can be clearly seen in Fig. 13(a) for particles of  $Z = 36$ . And Fig. 13(b) shows the measured spatial resolution as a function of the atomic number  $Z$  at  $U = 900$  V. It is evident that, at sufficiently high voltage, the resolution

worsens as  $Z$  increases. This deterioration occurs because particles with higher  $Z$  emit more  $\delta$ -rays under the same voltage condition. Therefore, to mitigate the impact of  $\delta$ -rays and improve the spatial resolution, the voltage must be moderately reduced for particles with a high  $Z$ . At a voltage of approximately 700 V, the drift chamber achieves its optimal spatial resolution of 35  $\mu\text{m}$  for  $Z = 36$ .

## IX. Summary

We have constructed the FDCs and RDCs for tracking of incoming and outgoing beams at the target area of ETF. The spatial resolution of FDCs (RDCs) is crucial for precise track reconstruction and particle identification. This article provides an overview of the construction details of FDCs (RDCs). Through beam tests, the effects of the time walk and  $\delta$ -rays on the drift time were investigated. The performance of the drift chamber was evaluated under different voltages, with a particular focus on the impact of  $\delta$ -rays on spatial resolution. The test results indicate that the impact of  $\delta$ -rays becomes more pronounced at high voltages and with ions that have large  $Z$ , leading to a degradation in the spatial resolution and the number of events with a multiplicity of 1 in the drift chamber. On the other hand, an insufficient voltage can lead to a decrease in the number of events with multiplicity greater than 0, resulting in fewer particles detected by the drift chamber. Therefore, an appropriate voltage must be chosen based on the nuclear charge number of the particles under investigation. At the optimal voltage, the FDCs (RDCs) achieve a resolution of approximately 35  $\mu\text{m}$  for heavy nuclei.

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