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Drift Chamber with cluster counting technique for CEPC

Wenyu Pan[a,b], Mingyi Dong[a,b,*], Linghui Wu[a], Guang Zhao[a], Yubin Zhao[a,b], Xiaohui Qian[a], Hongbin Liu[a], Gang Li[a], Shengjie Jin[c], Fei Huang[d], Zhefei Tian[e], Shuaiyi Liu[a,b], Zhenyu Zhang[e] and Shengsen Sun[a,b]

a Institute of High Energy Physics,
19B Yuquan Road, Shijingshan District, Beijing, China

b University of Chinese Acadeny of Scinces,
19A Yuquan Road, Shijingshan District, Beijing, China

c Northwest Normal University,
No. 967 Anning East Road, Lanzhou, China

d Liaoning University,
No. 66 Chongshan Middle Road, Huanggu District, Shenyang, China

e Wuhan University,
No. 299 Bayi Road, Wuchang District, Wuhan, China

E-mail: dongmy@ihep.ac.cn

Abstract:

To achieve the physics goals of the Circular Electron Positron Collider (CEPC), a tracking system combining a silicon tracker and a drift chamber is proposed. The drift chamber could provide excellent particle identification (PID) performance with cluster counting (dN/dx) technique. By measuring the number of primary ionizations along the particle trajectory, the dN/dx will significantly improve PID performance due to little sensitivity to Landau tails. Simulation study, including the detector and electronics responses as well as the reconstruction algorithm, is performed to optimize the detector design and performance. The results show the kaon and pion separation power with 1.2 m track for 20 GeV/c momentum can reach 3.2σ. Fast readout electronics was developed, and a detector prototype was tested with electron beam. The preliminary results validate the performance of the electronics and the feasibility of dN/dx method.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

[*]Speaker

PoS(ICHEP2024)1101

1. Introduction

The Circular Electron Positron Collider (CEPC) will produce 2.5×10^{12} Z bosons when operating at the Z pole, approximately $\sqrt{s} = 91.2$ GeV [1]. These large samples will enable rich flavor physics study [2]. Particle identification (PID), especially K/π separation with momentum up to 20 GeV/c, is crucial for the study of flavor physics and jets. In the CEPC detector disign, a tracking system that combines a silicon tracker and a drift chamber is an important option. The drift chamber will mainly be optimized for particle identification capability.

In drift chambers, dE/dx is a traditional PID method by measuring the energy loss and trajectory length of charged particles. But typically, dE/dx measurement for PID is limited to momentum less than 10 GeV/c. One limiting factor is Landau tails in the dE/dx distribution, which necessitates the use of a truncated mean and leads to loss part of the measured information. An alternative method is cluster counting (dN/dx), which measures the number of primary ionization over the track of particles as they pass through the drift chamber. Yield of primary ionization is a Poisson distribution, which is less sensitive to Landau tails than dE/dx. As a result, the resolution and separation capability of dN/dx measurement will be significantly improved.

Theoretical simulation study shows that the resolution of dN/dx can reach 2% - 3% at a track length of 1 m, which is about twice the resolution of dE/dx obtained by using the truncated average method. In recent years, due to the development of fast readout electronics and data transmission technology, some international high-energy physics experiments have conducted cluster counting related research. The MEG II experiment developed an ultra-low mass drift chamber, and its fast front-end electronics was designed to exploit the cluster timing technique [3]. In the design of the IDEA detector for future lepton colliders [4], a scheme of using a drift chamber for tracking and dN/dx based particle identification was also proposed, and corresponding simulation and experimental studies were carried out. In the CEPC detector design, the drift chamber is an important option for the tracker system, and it also employs cluster counting technique to obtain excellent PID capability, meeting the requirements of Higgs and flavor physics research.

The K/π separation power of a drift chamber based on the cluster counting technique depends on several effects, such as the cluster density, track length, detection efficiency, etc. They are, in general, defined by the detector parameters, including gas mixture, cell size, detector thickness, electronics performance, noise level, and so on. These parameters should be considered in the drift chamber design. In addition, the material budget of the drift chamber is also a key parameter with respect to the performance of the tracker.

2. Simulation study of ionization with the cluster counting technique

A waveform-based full simulation framework was developed for the cluster counting study. In the full simulation, the induced current signals from a drift chamber sense wire are simulated by using the Garfield++ code. The current signal waveforms are further digitized by imposing the electronics responses. Finally, a reconstruction algorithm is processed to count the number of primary peaks in the digitized waveforms.

2.1 Waveform generation

In the waveform generation, a drift chamber geometry is constructed in Garfield++. By setting the working gas mixture and working high voltage, the ionizations are simulated along the charged track trajectory. Produced electrons are transported in the electric and magnetic fields. Avalanches are generated close to the sense wires and induced current signals are created as the raw waveform. An example of the waveform is shown in figure 1.

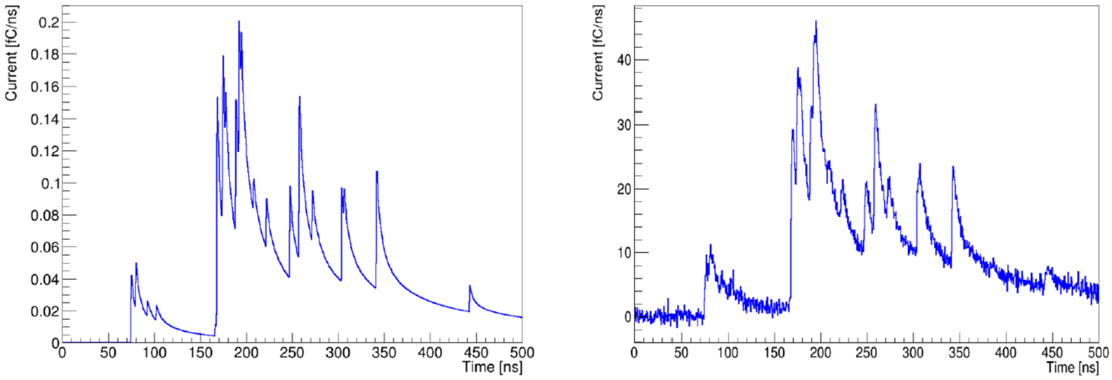

Figure 1: Raw waveform (left) and digitized waveform (right) of an induced current signal

2.2 Waveform digitization

The electronics responses have been considered in the waveform digitization.

(1) Fast preamplifiers are required in order to make the isolated peaks in a waveform distinguishable. The impulse response from a current-sensitive preamplifier has been calculated. The response can be parameterized by the amplification factor A and the time constant τ. While the time constant τ can reflect the width of the raw signal.

(2) The frequency response of the electronic noises is obtained by performing Fourier analysis on the noise waveforms from the experimental data. The noises in the time domain are recovered by taking inverse fast Fourier transform while assuming random phases on the frequency response, and they are added to the waveform.

(3) The sampling rate of the electronics is also considered. The analog waveform is digitized with a sampling rate of 1 GHz.

2.3 Waveform reconstruction

The reconstruction from the digitized waveform to primary ionization counts includes two steps. One is peak finding for both primary and secondary peaks. Discriminating peaks requires reducing the impact of noise. The other is Clusterization. Peak merging forms clusters, and the number of clusters is determined based on the detected peaks.

We have developed a reconstruction algorithm based on machine learning, including Long Short-Term Memory (LSTM)-based peak finding and Dynamic Graph CNN (DGCNN)-based clusterization [5]. Compared with traditional derivative-based algorithms, this algorithm has a lower fake rate and higher efficiency, especially in term of peak pile-up recovery. For simulated samples, a supervised model based on LSTM and DGCNN achieves a remarkable 10% improvement in separating K from π compared to the traditional derivative method.

2.4 Preliminary optimization of the drift chamber

By using the full simulation toolkit, we optimized the detector parameters and PID performance studies in terms of gas mixture, cell sizes and track length.

The gas mixture can affect several properties of ionization measurements. Small cluster density and slow drift velocity benefit the measurement, as the time interval between adjacent peaks is large. Small longitudinal diffusion can reduce the double-counting probability. Simulations have been performed with gas mixtures of different He and iC_4H_{10} ratios. According to the results, the gas mixture of 90% He + 10% iC_4H_{10} exhibits better K/π separation for the high momentum region.

The cell size, in principle, should not affect the PID significantly, as the resolution depends on the total track length. However, the cell size could have an impact on tracking and engineering. Simulations have been done to study the momentum resolution and wire tension with different cell sizes. The large cell size configuration can benefit from a better low-momentum p_T resolution and smaller wire tension. There is no significant difference in K/π separation for different cell sizes. Therefore, the selected cell size of 1.8 × 1.8 cm is reasonable.

The resolution of dN/dx is constrained by the total track length. K/π separation power with different track lengths has been simulated. According to the requirements of the CEPC detector and overall design of the tracking system, with 1.2 track length, the dN/dx resolution can achieve 2.5% - 2.6% and 2.6% - 2.7% for π and K respectively, and the seperation power for 20 GeV K/π is about 3.2σ, as shown in figure 2 and figure 3.

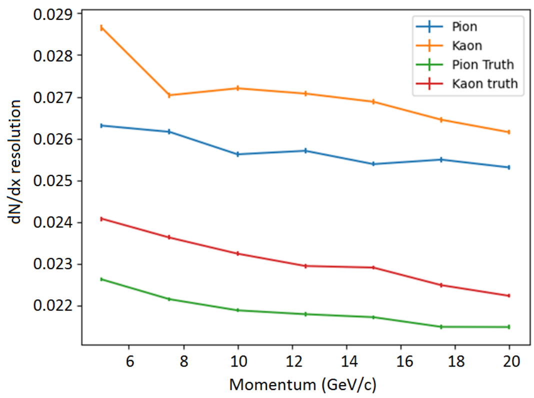

Figure 2: dN/dx resolution for pion and kaon with different momenta

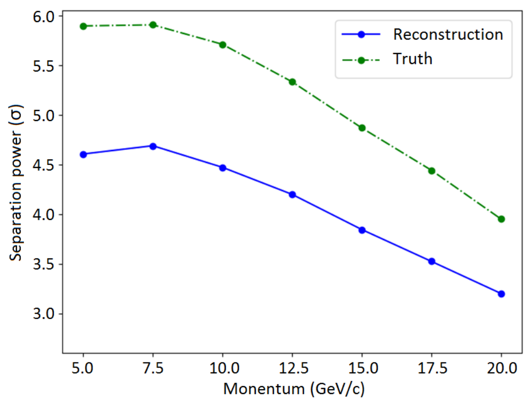

Figure 3: K/π separation power changes with momentum

3. Parameters of the drift chamber

Based on the simulation and optimization, the preliminary design parameters of the drift chamber are shown in table 1.

Table 1: preliminary design parameters of the drift chamber

Radius extension	600 -1800 mm
Length of outermost wires（cosθ=0.85）	5800 mm
Thickness of inner CF cylinder (for gas tightness)	200 μm
Thickness of outer CF cylinder (for gas tightness)	300 μm
Outer CF frame structure	Equivalent CF thickness: 1.8 mm
Thickness of end Al plate	20 mm
Cell size	~ 18 mm × 18 mm
Cell number	27623
Ratio of field wires to sense wires	3 : 1
Gas mixture	He / iC_4H_{10} = 90 : 10

The schematic diagram of the drift chamber structure is shown in figure 4. The length of the chamber is about 5800 mm, and the radius extension is from 600 mm to 1800 mm. The inner wall is a carbon fiber cylinder with a thickness of about 200 μm, and the outer support is a carbon fiber frame structure, including eight longitudinal hollow beams and eight rings, covered with a gas envelope for gas sealing. The aluminum end plates, with a thickness of about 20 mm, have a multi-stepped and tilted shape to reduce the deformation caused by wire tension. The results of finite element analysis show that under a load of about 1×10^4 kg, the support structure is stable, and the deformation is about 1 mm in the longitudinal direction.

There are 64 layers in the whole chamber. The cell size of about 18 mm × 18 mm is adopted with respect to the requirements of PID capability and momentum measurement. A sense wire is surrounded by eight field wires forming a square cell. The sense wires are 20 μm gold-plated tungsten wires, and the field wires are about 80 μm gold-plated aluminum wires. A gas mixture of 90% He and 10% iC_4H_{10} will be used. The simulation results show that the drift chamber with above parameters could achieve 3.2σ K/π separation at 20 GeV/c.

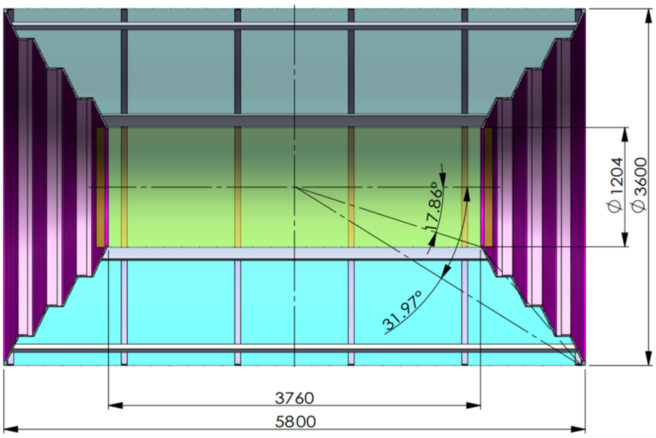

Figure 4: Schematic diagram of the drift chamber structure

4. Progress of detector R&D

High-performance readout electronics is critical for the measurement of the primary ionization. Fast preamplifiers with high bandwidth have been designed and developed. A test system was set up, including a preamplifier, a drift tube with a diameter of 30 mm, a CAEN DT5751 digitizer with 1 GHz sampling rate and two scintillators providing trigger signals. The system was tested with about 1.3 GeV electron beam. Figure 5 shows a typical waveform. The peaks contributed by different primary ionization are very clear and distinguishable, which indicates that the ratio of signal-to-noise is big enough. The test preliminarily validates the performance of the electronics and the feasibility of dN/dx method. The optimization of the fast preamplifiers and development of the ADC board with a sampling rate of 1.4 GHz are under progress. Meanwhile, a drift chamber prototype consisting of 12 layers of sense wires was designed, with a cell size of 18 mm × 18 mm. The drift chamber prototype aims to study and optimize the resolution of dN/dx.

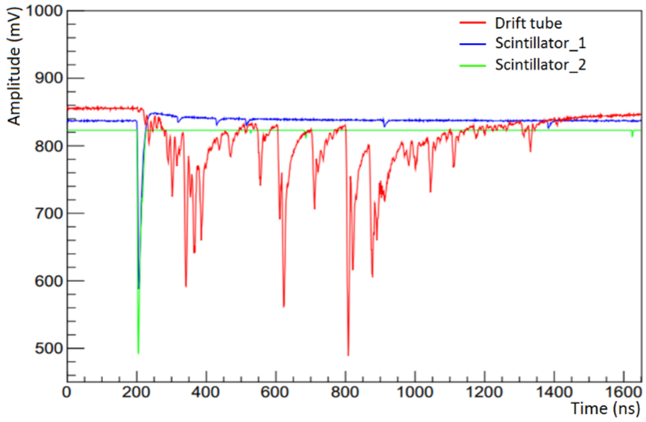

Figure 5: A typical tested waveform from the drift tube

5. Conclusion and plan

A drift chamber was proposed as a part of the tracker system of the CEPC detector and optimized to provide excellent particle identification capability. Simulation studies have shown that 3.2σ K/π separation at 20 GeV/c can be achieved with 1.2 m track length. Fast electronics development is under progress. Preliminary testing has validated the performance of the readout electronics and the feasibility of the dN/dx method. The cluster counting reconstruction algorithm based on deep learning shows promising performance for MC samples. In future studies, we will continue to fine optimize the detector design, and optimize deep learning algorithm and FPGA implementations. A multi-layer drift chamber prototype and testing system are developing to study and optimize the resolution of dN/dx. In addition, there are plans to construct a full-length prototype for testing the mechanical structure, manufacturing and performance.

Acknowledgements

This research was funded by Institute of High Energy Physics (Chinese Academy of Sciences) Innovative Project on Sciences and Technologies under Contracts No. E25456U210.

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