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High Precision Time Projection Chamber Technology R&D for Future e+e- Collider

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The Circular Electron Positron Collider (CEPC) is a large-scale scientific project proposed by the Chinese high-energy physics community. The CEPC accelerator Technical Design Report (TDR) has been released in 2023. The collider's energy scale ranges from Z-pole at 91 GeV to W^+W^- at 160 GeV, ZH at 240 GeV, and up to $t\bar{t}$ at 360 GeV. It will be a large Higgs and Z factory to allow precise measurements of their properties and searches for new physics beyond the Standard Model (SM). In the updated CPEC Physics and Detector Technical Design Report, the baseline design concept consists of a large gaseous Time Projection Chamber (TPC) as the main tracker detector (MTK). The TPC using high granularity pixel readout can provide up to thousands of 3-D space points, with a single hit resolution of approximately 100 μm in the r-φ plane, and it will be a promising technology, especially at the high luminosity Z-pole. In this paper, we will present the feasibility and progress of the high-precision TPC technology for CEPC Z-pole run and outline the next steps for developing pixelated TPC technology for CEPC Physics and Detector TDR.

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1. Introduction

The Circular Electron Positron Collider (CEPC) proposed by the Chinese high-energy physics community is a large-scale scientific project. The CEPC accelerator Technical Design Report (TDR) [1] has been released in 2023. The CEPC accelerator TDR confirms that the CPEC will be a double-ring e^+e^- collider with a 100 km circumference, and the collider's energy scale ranges from Z-pole at 91 GeV to W^+W^- at 160 GeV, ZH at 240 GeV, and up to $t\bar{t}$ at 360 GeV. The achieved luminosities at these energy scales will produce large samples of Higgs, W, and Z bosons to allow precise measurements of their properties. In the updated CEPC Physics and Detector TDR, the baseline design concept of the tracker system consists of a large gaseous Time Projection Chamber (TPC) as the main tracker detector (MTK), along with silicon track detectors inside and outside the TPC to improve the track momentum resolution. The TPC in the CEPC Physics and Detector TDR will be a cylindrical drift volume with an inner radius of 0.6 m, an outer radius of 1.8 m, and a half-length of 2.9 m. This design aims to enhance the tracking acceptance (cosθ ~0.98) and provide thousands of 3D measurement points of charged tracks using 500 μm $\times$ 500 μm pixel readout.

Recently, extensive R&D has been conducted for the TPC track detector in the CERN DRD1 Collaboration and LCTPC Collaboration. Extensive experiments and simulation studies have shown that the pixel readout TPC technology offers numerous advantages compared to the traditional pad readout (e.g. 1 mm $\times$ 6 mm). According to the theoretical TPC hit resolution formula of the pixel and pad readout [2, 3], the resolution of the pad readout with rectangular pads depends on the angle (ϕ) of the track with the pad rows and the resolution of the pixel readout does not. So the pixel readout TPC can be not only advantageous for tracks at an angle with the pad rows but also for the forward tracks ($\theta \leq 30°$) due to the number of pad rows reduction while the number of pixel hits does not reduce as much. The powerful Particle Identification (PID) capability is another remarkable feature of TPC. There exist considerable fluctuations in ionization. The dE/dx measured by pad readout will be a Landau-like distribution with a long tail, and the typical dE/dx resolution can achieve 5% [4]. The pixel readout TPC can significantly improve the PID capability using cluster counting method in space [5]. Furthermore, using pixel readout can operate in higher count rate (~ 3.6 MHz/mm^2/s) environment [6], especially for high luminosity (~ 10^{36}/cm^2/s) Z-pole mode.

This paper will present the feasibility and progress of the pixel TPC technology for CEPC Z-pole run and outline the next steps for developing pixelated TPC technology for CEPC Physics and Detector Ref-TDR.

2. Feasibility study of the pixel readout TPC at high luminosity Z pole

Under the CEPC high luminosity Z-pole operation, it will produce massive quantity hits in TPC drift volume, including physics events and beam backgrounds. Correspondingly, the TPC as a tracker detector needs to provide perfect position resolution and handle a high count rate. One of the key issues is evaluating the pixels' hit density and occupancy caused by the beam-induced background, and distortions caused by space charge effect. The following subsections will evaluate the hit density and distortion at CEPC TPC at Z-pole mode.

2.1 Simulation flow of beamstrahlung

Given the high luminosity of Z-pole, beamstrahlung [7] is one of the most important sources of beam-induced background. There are about 680 e^+e^- produced via the beamstrahlung process in each bunch crossing (BX). It will interact with the beam pipe or other materials within the TPC. Thus, these secondary particles will incident TPC and cause large amounts of hits and positive ions that might degrade the TPC performance. A complete simulation flow, as shown in Figure 1, was established to study the beamstrahlung and performance of TPC under high luminosity Z-pole. 10000 BX have been simulated by Guinea-Pig++ [8] and exported to CEPC Software (CEPCSW) for full detector simulation. Then, hits and energy deposits in TPC volume are extracted to evaluate the hit density and space charge distribution.

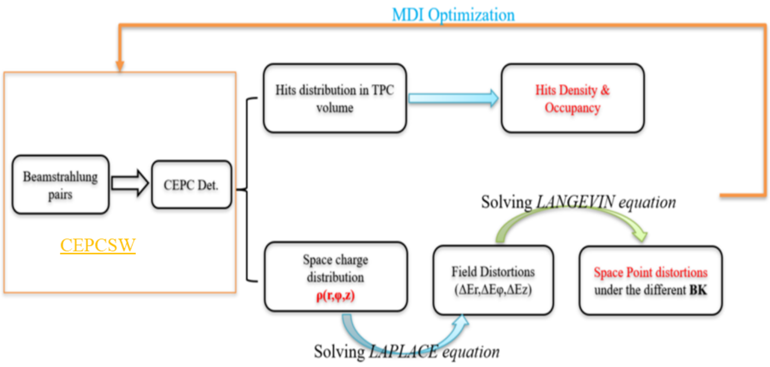


Figure 1: Overview of the simulation flow of CEPC beamstrahlung.

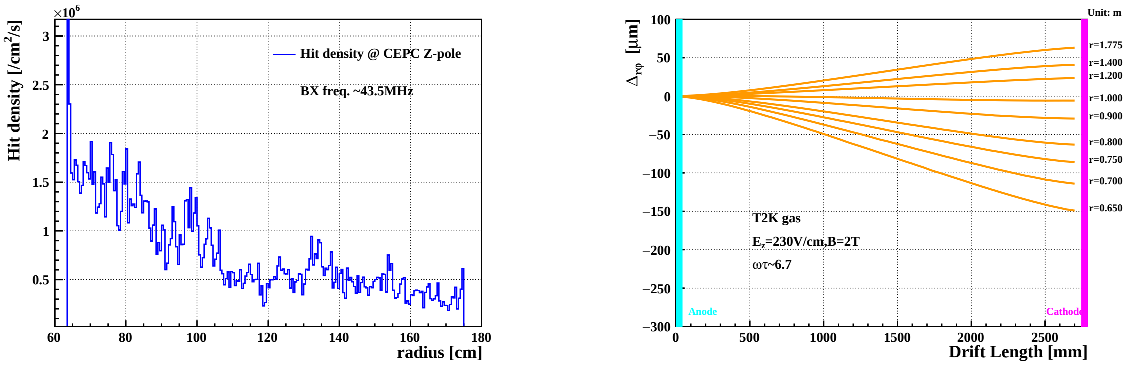
2.2 Hit density and distortion of pixel readout TPC

All hits generated by 10000 BX pairs have been extracted to calculate the distribution of the average hit density. Given the 23 ns BX spacing time (Bunch frequency~43.5 MHz) at Z-pole, the hit density in the radial direction is given in Figure 2a. The peak hit density is 2×10^6 /cm^2/s, corresponding to the TPC innermost layer of the TPC. So the maximum hit rate for a single pixel (500 μm $\times$ 500 μm) is 5×10^3/s. The sampling rate of the TPC DAQ is 40 MHz. The drift velocity V_d can reach ~8 cm/μs in T2K gas (Ar/CF4/*i*C4H10=95/3/2). So each hit occupies about $V_d\times$ 25 ns = 2 mm in the z direction. The TPC can be considered equivalently to be filled with 3-D small readout voxel with 0.25 mm^2 in the xy direction and 2 mm size in the z-direction. For the voxel occupancy, the time window of the front-end electronics is relevant. Considering 300 ns time window, the maximum voxel occupancy (VO) in the inner layer of TPC is only 1.5‰, which is safe for the Z-pole operation.

The space charge density had been calculated from the hit density, weighted by the energy deposit. The number of primary ions produced in each hit is determined by the ratio of energy deposit to effective ionization potential of Argon (26 eV) [9]. The peak space charge density ρ_{sc} is about 0.32 nC/m^3. Then, field distortions (E'_r,E'_φ,E'_z) had calculated by solving the *Poisson* equation based on Green's Function method [10]. The distortion at different drift length L is given by the following equation, derived from *LANGEVIN* equation,

$$\Delta_{r\varphi} = \int_0^L \frac{\omega\tau}{1+\omega^2\tau^2} \times \frac{E_r'}{E_z'} dl \tag{1}$$

where $\omega\tau \equiv eB/m$, τ is the mean free time of electrons. The value of $\omega\tau$ is about 6.7 under 2 T magnetic field, simulated by Garfield++ [11]. As shown in Figure 2b, the distortion gets larger and larger with the increase of drift length. The maximum distortion can reach an order of 150 μm.



(a) Hit density distribution in radius direction at CEPC Z-pole.

(b) The distortion in r-φ direction as a function of drift length.

In conclusion, we conducted some feasibility studies with pixel readout TPC and investigated the voxel occupancy and distortion at CEPC Z-pole. It shows that the pixel readout TPC can handle the high-count environment. However, the space charge effect will deteriorate TPC performance under Z-pole, which needs to be further investigated.

3. Developments of pixel TPC modules and prototype

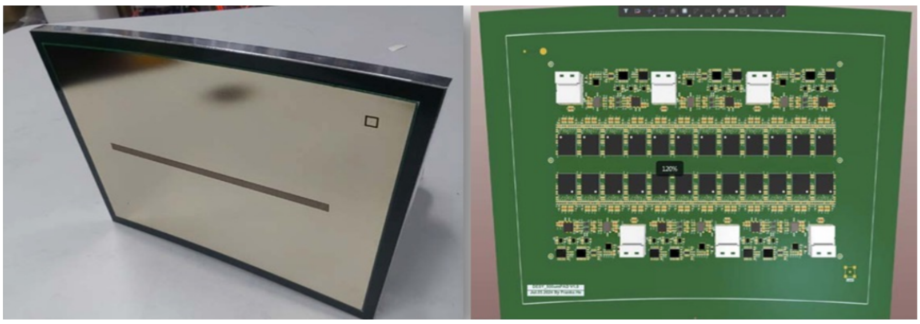


Figure 3: The photon of TPC module for CEPC (left) and the design of readout PCB (right).

In CEPC Ref-TDR, there are 248×2 readout modules at the two endplate. We have developed several TPC readout modules, glued with aluminum back frames, which can mounted in the large TPC prototype (LP) at DESY [12] and tested using electron beam. As shown in Figure 3 left, there are 3000 readout pixels with 0.5 cm × 15 cm active area in the middle of the module. Each pixel size is 400 μm × 400 μm and the interval between neighboring pixels is 100 μm. The 3000 channels will be connected to 24 low power consumption ASIC chips (see in Figure 3 right). The TEPIX chip is a particle detector readout chip with 128 channels for simultaneous energy and time measurements developed by Tsinghua University. Some updated experimental studies shows that the chip can work well tested in the laboratory. The power consumption was about 200 mW/cm^2 and the equivalent noise charge (ENC) was 300 e$^-$ at standard input capacitance. Moreover, a small TPC prototype with 50 cm drift length has been designed. The modules can also be installed at the endpalte of this prototype for testing. Commission of TEPIX chips and TPC modules with Micromegas detector will be studied in the laboratory using 266 nm UV laser.

4. Conclusion

In this paper, pixel readout TPC motivations and advantages for CEPC Ref-TDR are discussed initially. Some feasibility studies have demonstrated that pixel TPC can operate at CEPC high luminosity Z-pole mode based on full simulation results of beam background. For the TPC modules and prototype R&D, readout modules assembled with TEPIX chips have been fabricated. More detailed experimental studies using 266 nm UV laser and electron beams are ongoing.

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