Poster ID: 35

Investigating Beam Backgrounds in TPC and Developing Pixelated TPC Prototype for CEPC

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Introduction

In the latest design of the Circular Electron-Positron Collider (CEPC) detector, the time projection chamber (TPC) has been chosen as the main tracker detector (MTK). As shown in Fig. 1, 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 ($\cos\theta \sim$0.98) and provide thousands of 3D measurement points of charged tracks using 500 μm $\times$ 500 μm pixel readout.

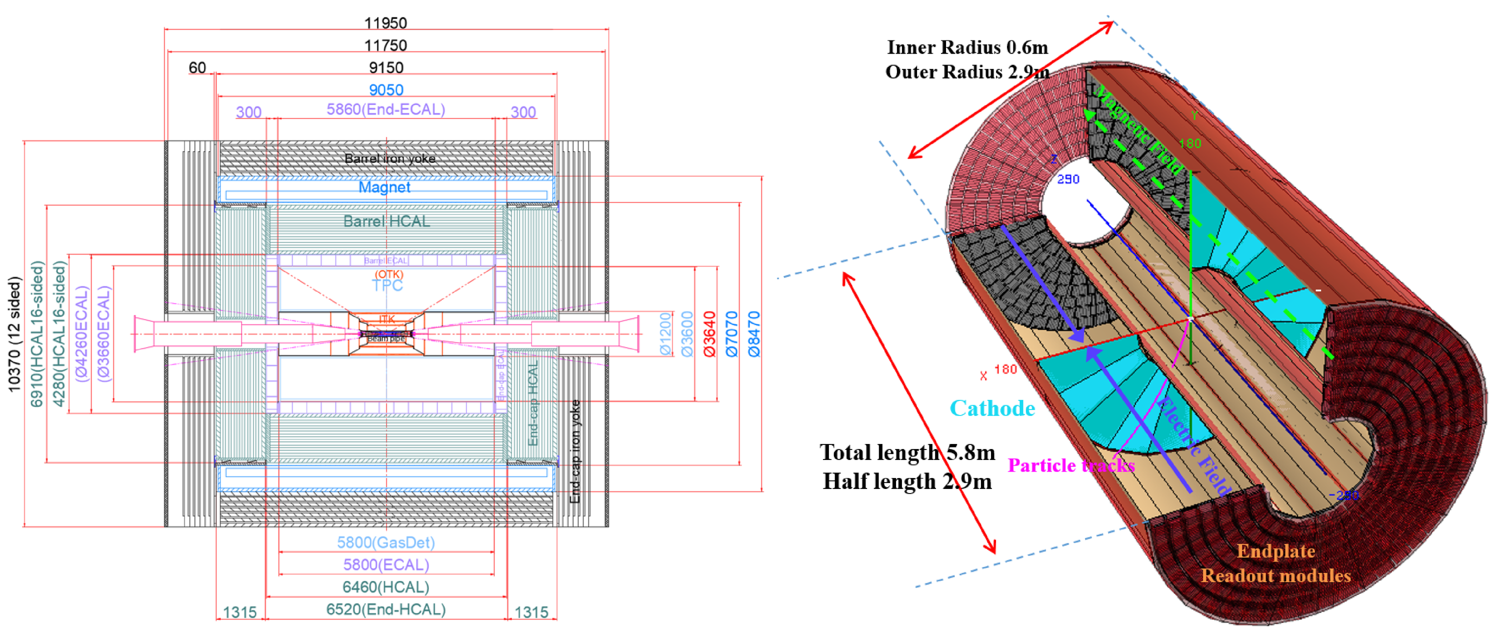

Figure 1. The detector layout of CEPC Ref-TDR (left) and The geometry of TPC at 3-D view (Right)

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 poster, we will present the feasibility and progress of the high-precision TPC technology for CEPC and outline the next steps for developing pixelated TPC detector for CEPC Physics and Detector TDR.

Investigation of beam backgrounds in TPC

Under the CEPC different operation modes, it will produce massive quantity hits and ions 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. As shown in Fig. 2, the ions in TPC volume can be generated by the following three different processes:

- Physics events: $H \rightarrow ss/cc/sb, Z \rightarrow q\bar{q}$ ...(high P_T)
- Beam Backgrounds: Beamstrahlung (luminosity related), Touschek scattering, Beam-Gas ...
- Ion back flow from the MPGD readout modules

Beamstrahlung is one of the most important sources of beam-induced background. There are about 1300/680 e^+e^- produced for Higgs/Z-pole mode 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.

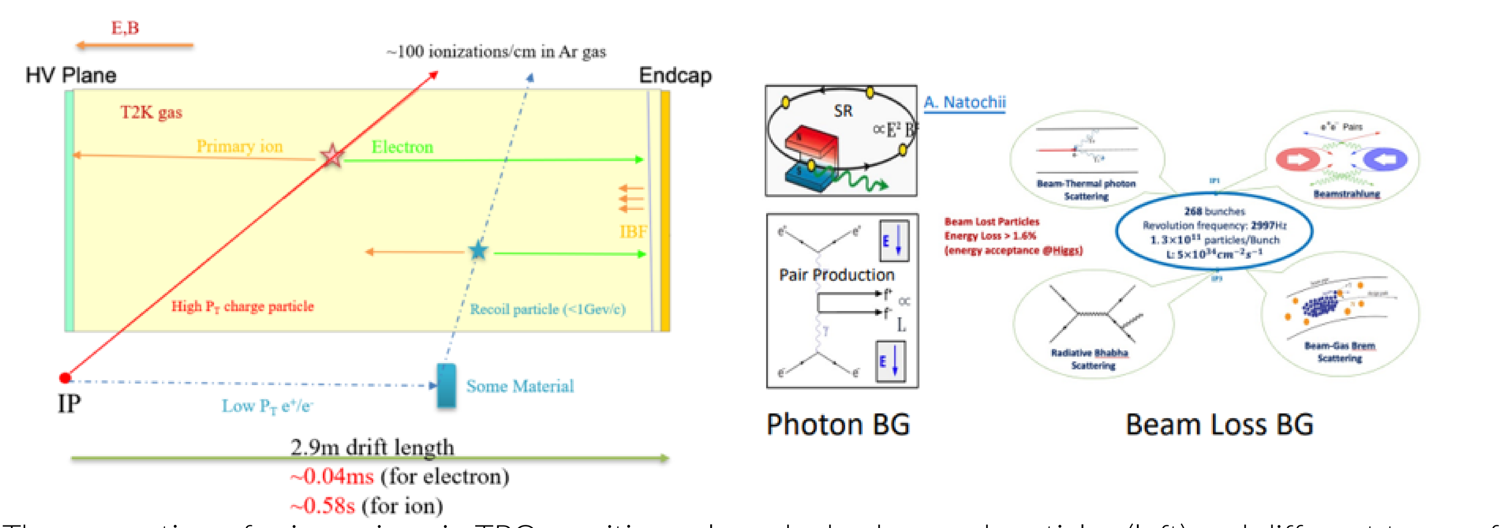

Figure 2. The generation of primary ions in TPC sensitive volume by background particles (left) and different types of beam backgrounds (Right)

A complete simulation flow was established to study the beamstrahlung and performance of TPC. 10000 BS files been simulated by Guinea-Pig++ 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.

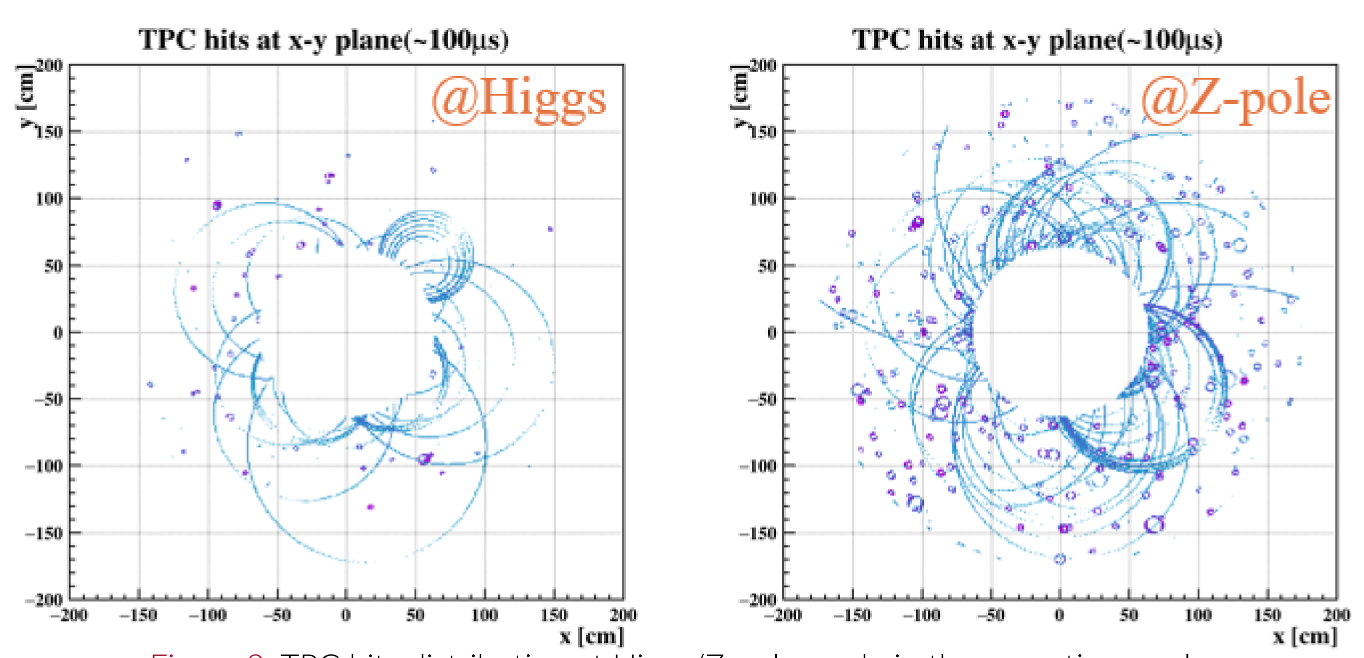

Figure 3. TPC hits distribution at Higgs/Z-pole mode in the same time-scale

Fig. 3 shows the TPC hits distribution caused by beamstrahlung at Higgs and Z-pole mode in the same time-scale. The hit density at Higgs mode is much lower than Z-pole due to smaller BX frequency. Detailed results about hit density and voxel occupancy at two operation mode are given in Table 1:

Table 1. Simulation result of hit density, VO and max. space charge density in TPC

Collider Detector Model	TDR_o1_v01	TDR_o1_v01
Beamstrahlung pairs	Z-pole(91GeV)	Higgs(240GeV)
BX freq.	1/23 ns	1/355 ns
Hit density [MHz/cm^2]	1.8	0.4
Voxel Occupancy	1.5×10^{-3}	2.8×10^{-4}
average primary ρ_{ion} [nC/m^3]	0.11	0.02
max (steady state) [nC/m^3]	0.32	0.06

Space charge effect and Distortion in TPC

The space charge density had been calculated from the hit density, weighted by the energy deposit. The distorted electric field caused by primary ions can be solved analytically based on Green's function.

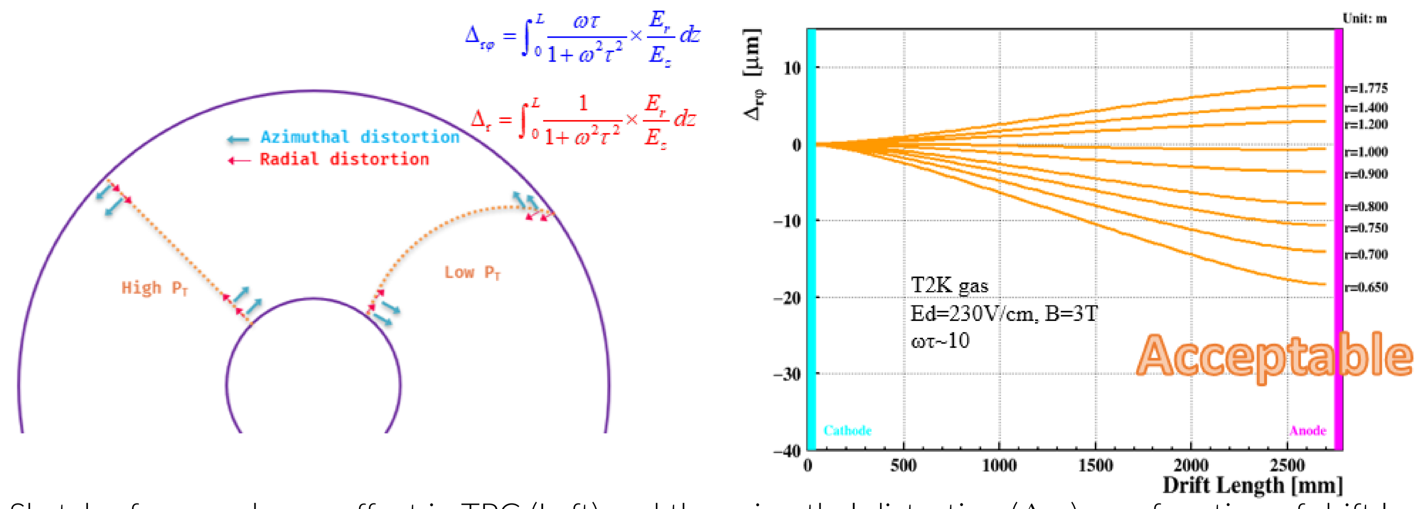

Figure 4. Sketch of space charge effect in TPC (Left) and the azimuthal distortion ($\Delta_{r\varphi}$) as a function of drift length (Right)

As shown in Figure 4, azimuthal distortion has more significant impact on both high/low P_T tracks compared to radial distortion. The maximum $\Delta_{r\varphi}$ is only $\sim$ 20 μm at Higgs mode, which is acceptable. However, the TPC performance will get $\sim\times5$ degrade under Z-pole run, which needs further optimization on MDI design.

Developments of pixel TPC modules and prototype

In CEPC Ref-TDR, there are 248$\times$2 readout modules at the TPC endplate. We have developed several TPC readout modules (See Fig. 5), glued with aluminum back frames, which can mounted in the large TPC prototype (LP) at DESY (see Fig. 6 right) and tested using electron beam.

Pixel TPC readout module

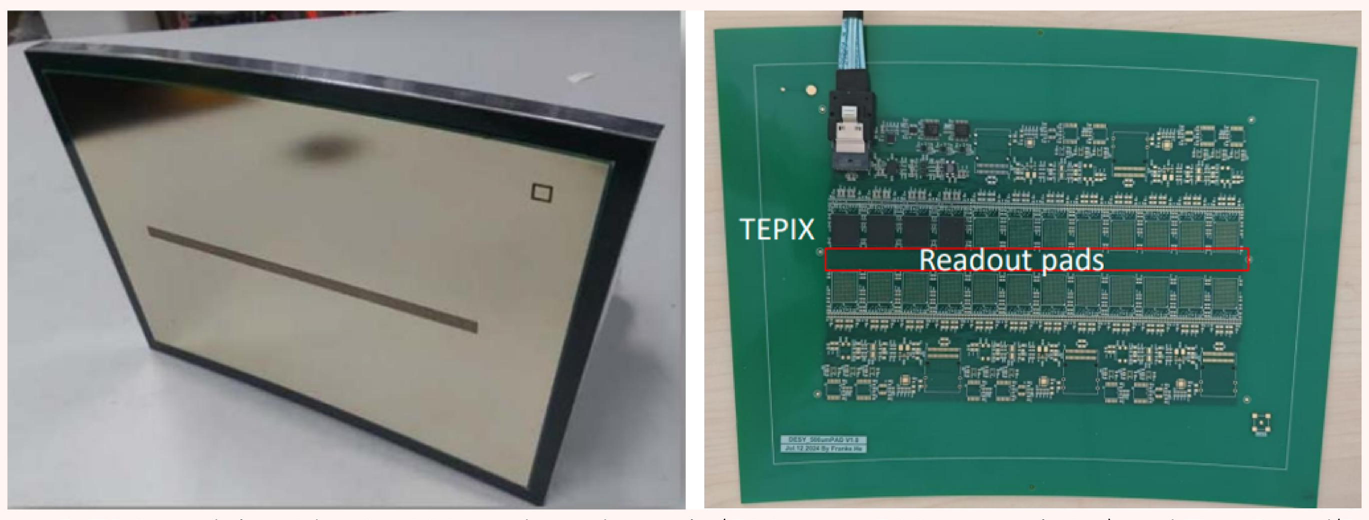

Figure 5. TPC module with 10$\times$300 readout channels (500μm $\times$ 500μm pixel size) and Test Board(Right)

Pixel TPC prototype design and Large TPC prototype at DESY

Moreover, a small TPC prototype with 50 cm drift length has been designed (See in Fig. 6 left). The modules can also be installed at the endpalte for testing using 266 nm UV laser beam.

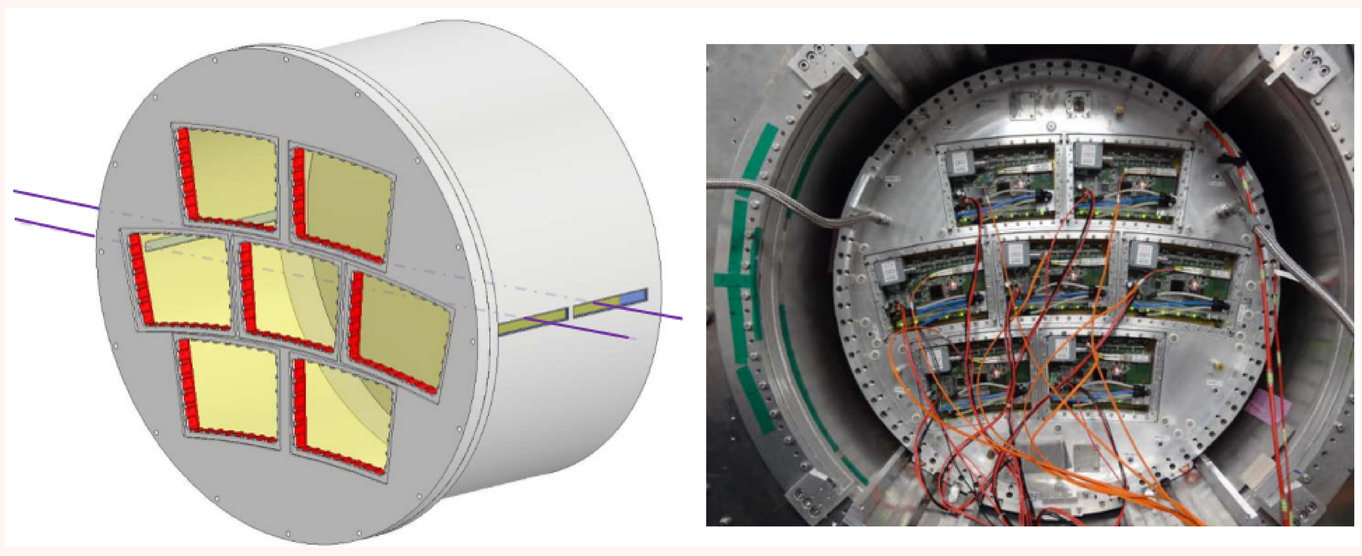

Figure 6. The design of pixel TPC prototype with 7 modules at the endplate (Left) and Large prototype at DESY (Right)

The 3000 channels will be connected to 24 low power consumption ASIC chips, named TEPIX, which is a particle detector readout chip with 128 channels for simultaneous energy and time measurements developed by Tsinghua University.

FEE ASIC chip test result and Offline analysis program:

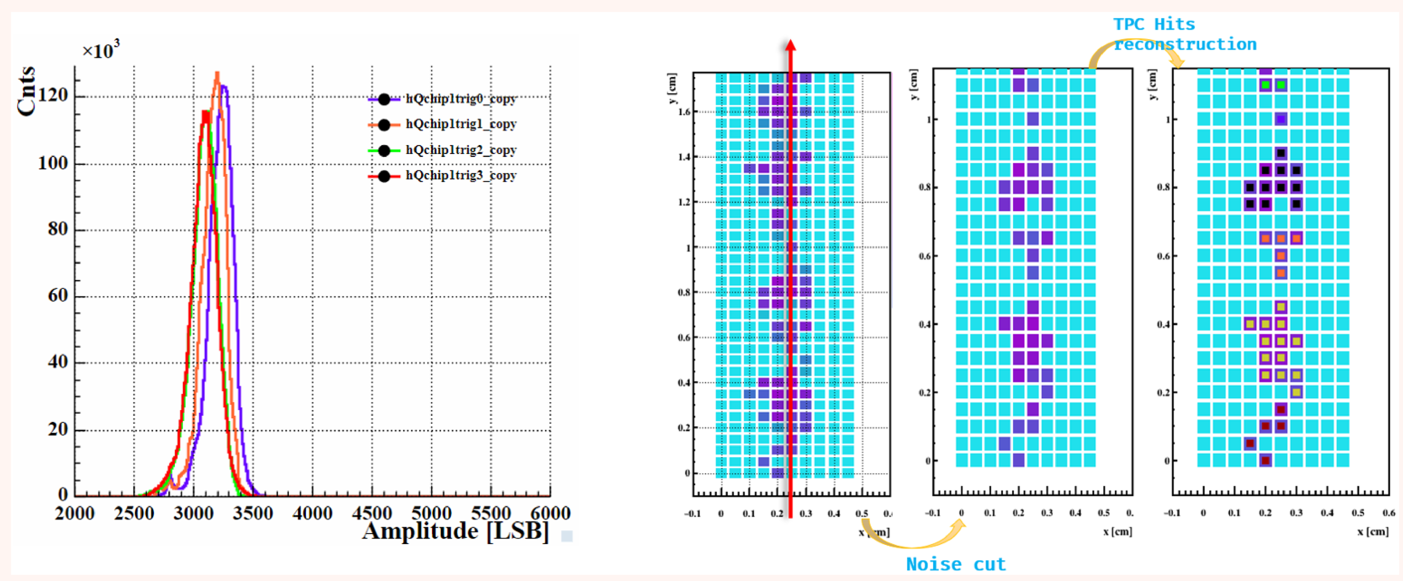

Figure 7. The amplitude distribution of TEPIX chips (Left) and diagram of the pixel TPC hit reconstruction process (Right)

- **Power consumption and Noise** $\sim$ 0.5 mW/ch, $\sim$ 300 e^-
- **Gain:** 314.2 LSB/fC
- **Get expected energy value according to the charge injected**. The Energy distributions of TEPIX chips are shown on Fig. 7 left.
- **Offline analysis program for pixel TPC prototype have been developed.** The **json** configuration file can be used to unpack the raw binary data, reconstruct TPC hits and tracks, etc. Fig. 7 right shows the diagram of hit reconstruction process.
- Beam test of the pixelated readout TPC prototype is underway in preparation. (November 2024 and January 2025)

Concusion

1. Pixel TPC can either operate at CEPC Higgs or high luminosity Z-pole mode based on full simulation results of beam backgrounds.
2. For the TPC modules and prototype R&D, readout modules assembled with TEPIX chips have been fabricated.
3. More detailed experimental studies using 266 nm UV laser and electron beams are ongoing.