Feasibility study of TPC at electron positron colliders at $Z$ pole operation

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ABSTRACT: TPC is a promising technology for the future electron positron colliders. However, its application might be limited at high event rate and high hit occupancies. In this paper, we study the feasibility of using TPC at the circular electron positron collider (CEPC) at $Z$ pole using full simulated $Z \to q\bar{q}$ samples, by evaluating the local charge density and voxel occupancy at different TPC parameters. Our study shows that the TPC could be applied to the CEPC $Z$ pole operation if backflow ion is controlled to per mille level. We also find that the distortion is considerable for the FCC-ee $Z$ pole operation. And a few approaches are proposed to reduce the distortion.

KEYWORDS: Time projection Chambers (TPC); Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc)

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1 Introduction

The CEPC is a proposed electron positron collider after the Higgs discovery. It will be applied as a Higgs factory and a Z factory. As a Higgs factory, it will be operated at 240 GeV center of mass energy, produce 1 million Higgs bosons in 10 years and measure the Higgs couplings to 0.1%–1% level accuracy [1]. It will also be operated at the Z pole and produce approximately 10 billion Z bosons each year. The typical cross-sections and event rates for the nominal CEPC accelerator parameters are given in table 1.

| Table 1. Typical parameters and productivity of the CEPC [2]. |
|-------------------------------------------------------------|
| Parameter                    | Higgs runs | Z pole |
| Center of mass energy (GeV) | 240        | 91     |
| Instant luminosity (cm⁻²s⁻¹) | 2 x 10³⁴   | 2 x 10³⁴ |
| Signal cross-section         | 200 fb     | 30 nb for Z → q̅q̅ |

TPC has been widely used in high energy physics experiments [3–6]. It provides high-efficiency track finding, precise momentum measurement, and has low material budget. In addition, TPC provides good dE/dx measurement, providing essential information for particle identification. These benefits are highly appreciated for the CEPC physics program [1].

The CEPC conceptual detector is a Particle Flow Algorithm (PFA) oriented detector designed following the ILD detector [3], where TPC is used as the main tracker. The geometry of the CEPC conceptual detector is adjusted to the CEPC collision circumstance. At a center of mass energy close to the Z mass, most of the TPC hits are induced by Z → q̅q̅ events. The event rate of Z → q̅q̅ process is 600 Hz per IP for the CEPC Z pole operation [1]. Another future electron positron collider, the FCC-ee [7], has much aggressive beam parameters and the event rate of Z → q̅q̅ is 60 kHz, two orders of magnitude higher than that of CEPC. Such a high event rate makes stringent
requirement for the TPC. It is crucial to study the feasibility of using TPC at these electron positron colliders at their Z pole operation.

On the other hand, the response of TPC is slow comparing to the silicon detectors, as the electrons generated in the primary ionization need to drift toward the endcap to create electronic signals. The position measurement of TPC is limited by the back flow ions, i.e., ions generated in the amplification back flowing into the gas volume. These spatial ion charges will distort the electric field and induces uncertainties to the hit position measurements.

The performance of TPC is mainly limited by local charge density and the voxel occupancy. The local charge density is required to be smaller than the intrinsic TPC spatial resolution of 100 µm in φ−direction, so that the resolution of TPC readout pixel will not be dominated by the distortion. And the voxel occupancy should be much smaller than 1. In this paper, we evaluate these effects with full-simulated $Z \rightarrow q\bar{q}$ data, extract the analytic format of corresponding distributions and parameterize them to TPC and luminosity parameters. Taking reference to the empirical formula on these parameters, we conclude that the TPC works at nominal instant luminosity at CEPC, if the charge induced by back flow ion is only 1 order of magnitude higher than that of primary ionization.

2 Simulation and sample

We simulate 9 thousand $Z \rightarrow q\bar{q}$ events with Mokka [8], the Geant4 simulation package [9] for CEPC detector optimization study. Giving a $2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ instant luminosity, this sample is corresponding to a data-taking period of 15 seconds.

The detector geometry we used in simulation is the CEPC conceptual detector model, the conceptual detector modified from the ILD detector geometry. Designed following the principle of particle flow algorithm, the conceptual detector uses low material tracking system and high granularity calorimeter system. Both ECAL and HCAL are installed inside the solenoid magnetic field to reduce the dead zone.

CEPC conceptual detector uses TPC as main tracker. The TPC has an inner radius of 330 mm, an outer radius of 1808 mm and a half-length of 2350 mm. The readout pixel is of 1 mm along the $\phi$−direction and 6 mm along the $r$−direction. The boundary of the field cage is located at an inner radius of 354 mm and an outer radius of 1748 mm. The readout pixels begin at a radius of 380 mm and end at a radius of 1713 mm. Along the $r$−direction, the TPC is divided into 220 layers. The working gas of the TPC is the 1 atm T2K gas, which is composed of 95% argon, 2% isobutene and 3% CF4.

3 Spatial charge distribution in the TPC (physics picture)

The ions in the TPC volume are induced by primary ionization and the ion back flow. Once a charged track is sailing through the TPC volume, it induces primary ionizations along its trajectory. Driven by the drifting electric field, the electrons are drifted to the endcap and the ions to the central HV plane. Once the electrons arrive the endcap, they creates electronic signals through the cascade amplification with a typical gain of 3000–6000 [10], depending on different detector technology. A fraction of the ions generated in the amplification procedure can back flow into the TPC volume, inducing the back flow ions. Since the ion is much heavier than the electron, the drift velocity of ion
is typically four orders of magnitude smaller than that of the electron. Therefore, for a given track, the ions generated in primary ionizations are located along the track helix, while the back flow ions forms effectively a projection of the initial track to the transverse plane, as shown in figure 1.

At the CEPC TPC, the primary charge density is of around $9.4 \text{ primary ions mm}^{-1}$ along the track [11]. The drift velocity is $80 \text{ km s}^{-1}$ for the electrons and $5 \text{ m s}^{-1}$ for the ions. Giving the benchmark luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ at CEPC $Z$ pole operation, the $Z \rightarrow q\bar{q}$ events have an event rate of $600 \text{ Hz}$. Since the TPC half $z$ is $2.35 \text{ m}$, there will be roughly $600$ disks located evenly in the TPC volume, i.e., $300$ disks at each side of the HV plane, each corresponding to the back flow ions induced by one $Z \rightarrow q\bar{q}$ event, as shown in figure 1. These disks are then drifted toward the central HV plane with the velocity of ions.

The distribution of ions can be described by projective charge density and local hit density. The latter is described by the voxel occupancy. In the following part of this paper, we resolve the spatial distribution of the hits and charges, from which we calculated the distortion at different parameter configurations.

4 Hit map and voxel occupancy

The projective TPC hit map of $9 \text{ thousand } Z \rightarrow q\bar{q}$ events is shown in figure 2, which exhibits an uniform distribution along the $\phi$-direction. The hit density decreases with increasing the radius.

The distribution of hits per event is given in figure 3. 60 million hits are generated in this sample. On average, each $Z \rightarrow q\bar{q}$ event will induce $6900$ hits in the TPC volume and the most probable value of the number of hits is about $4000$. The dependence of projective hit density and radius is shown in the left plot of figure 4. The sample is normalized to the projective hit density of one $Z \rightarrow q\bar{q}$ event in half the TPC. The average hit density is $5 \times 10^{-4} \text{ mm}^{-2}$. And the peak hit density is $2 \times 10^{-3} \text{ mm}^{-2}$, corresponding to the inner most layer.

The DAQ sampling rate of the TPC is $40 \text{ MHz}$. The electron drift velocity divided by the DAQ sampling rate gives $2 \text{ mm}$. Therefore, the TPC can be considered equivalently to be filled with
Figure 2. Projective hit map on the X-Y plane for $Z \rightarrow q\bar{q}$ events. The $z$ axis represents the hit density in unit $\text{mm}^{-2}$ and it is normalized to one $Z \rightarrow q\bar{q}$ event.

Figure 3. Number of hits per $Z \rightarrow q\bar{q}$ event distribution.

three-dimension small readout modules with 2 mm size in $z$-direction. A small equivalent readout module is called a voxel. The TPC readout pixel is 1 mm along the $\phi$-direction and 6 mm along the $r$-direction. Therefore, a voxel has a size of $1 \text{ mm} \times 6 \text{ mm} \times 2 \text{ mm} = 12 \text{ mm}^3$. The voxel occupancy is defined as the number of voxels with signal, divided by all voxels in the TPC. The TPC has around 1.4 million readout modules on each endcap. The number of readout pixel per second in half of the TPC is $5.9 \times 10^{13}$, which is the number of readout pixel in the end cap multiply by the DAQ sampling rate. At the CEPC benchmark luminosity, 600 $Z \rightarrow q\bar{q}$ events will be generated in 1 second, and 2 million TPC hits will be induced by these events in half of the TPC. Considering on average each hit occupies approximately 10 voxels along the time direction, the number of voxel
Figure 4. Hit density (left) and charge density (right) as a function of radius. The distributions are normalized to one $Z \rightarrow q\overline{q}$ event.

with signal is $2 \times 10^7$ s$^{-1}$. The beam bunches of the CEPC are distributed evenly along the tunnel. The average voxel occupancy is then $3.4 \times 10^{-7}$ s$^{-1}$.

The voxel occupancy is also a function of the radius and it should simply follow the distribution of local hit density, as shown in the left plot of figure 4. Given the fact that the peaking hit density is 4 times larger than the average density, the maximal voxel occupancy located at the TPC inner most layer, corresponding to a value of $1.4 \times 10^{-6}$ s$^{-1}$.

The voxel occupancy is proportional to the instant luminosity. Therefore, at the FCC-ee benchmark luminosity, the maximal voxel occupancy will be increased by 2 orders of magnitude, reaching the level of $1.4 \times 10^{-4}$ s$^{-1}$.

The CEPC proposes also the partial double ring design, where bunches are zipped into bunch trains with the typical length of 1km, two orders of magnitude smaller than the accelerator circumference. In this case, the voxel occupancy would also be increased by two orders of magnitude, reaching $1.4 \times 10^{-4}$ s$^{-1}$ at the inner most layer.

To conclude, for the CEPC $Z$ pole runs with the TPC of the conceptual detector, the voxel occupancy takes its maximal value between $1.4 \times 10^{-4}$ s$^{-1}$ to $1.4 \times 10^{-6}$ s$^{-1}$, which is safety for the $Z$ pole operation.

5 Projective charge density and distortion

The projective charge density could be calculated from the local hit density, weighted by the distance of the adjacent hits along the trajectory. It is also assumed that on average 9.4 ions are created per millimeter [11]. The projective charge density of primary ions in half TPC volume is shown in the right plot of figure 4. Through fitting the data using an empirical function,

$$\rho = 9.135 \times 10^{-3} \frac{r}{mm} - 97.87 - 4.166 \times 10^{-6} \text{ [fC mm}^{-2}]$$

is used to describe the projective charge distribution, where $r$ is the radius.

The projective charge density can also be regarded as the surface charge density of an ion disk. The space charge density is proportional to the surface charge density of the disks and the
disk number density along the z axis. The latter is the $Z \rightarrow q\bar{q}$ event rate divided by the ion drift velocity. The space charge density should also be proportional to the luminosity and the average number of back flow ions generated per primary ionization. Therefore, multiplying them together, the space charge density can be parameterized by:

\[
(1 + k) \frac{L}{V_{\text{ion}}} \times \rho \times R = (1 + k) \frac{L}{V_{\text{ion}}/\text{(m s}^{-1})} \left( \frac{2.74 \times 10^{-3}}{r/\text{mm} - 97.9} - 1.25 \times 10^{-6} \right) \text{[fC mm}^{-3}]\tag{5.2}
\]

where $L$ is the luminosity normalized to $1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, $V_{\text{ion}}$ is the ion drift velocity, $R$ is the $Z \rightarrow q\bar{q}$ event rate under the luminosity of $1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, $r$ is the radius, and in the factor $(1 + k)$, 1 corresponds to the primary ion and $k$ is the electron multiplication gain at the amplification times the fraction of ions which can flow back. At the current TPC R&D, the typical values of these parameters are:

- $V_{\text{ion}}$: (5–10) m s$^{-1}$.
- $k$: 5–100 depending on the control of back flow ions.
- $R$: 300 Hz.

These ion charges induce an electric field on top of the existing electromagnetic field. The electrons generated by the track ionization is drifted accordingly. Comparing to the case of zero ion charge density, the ion-induced electric field will cause a hit position distortion along $E \times B$ direction, i.e., $\phi$-direction. The distortion along the $\phi$-direction in a local volume can be expressed as:

\[
\Delta l = \omega \tau \frac{1}{1 + (\omega \tau)^2} \times \frac{E_r}{E_z} \Delta z, \tag{5.3}
\]

where $\Delta l$ is the distortion along the $\phi$-direction, $\Delta z$ is the drift length along the z-direction, $E_r$ and $E_z$ are the electric field along the $r$-direction and $z$-direction, and $\tau$ is the mean free time of electrons. $\omega \equiv eB/m$, where $B$ is the magnetic field, $e$ and $m$ are the charge and mass of electron. The value of $\omega \tau$ is quite large using the T2K gas and it vary with gas pressure and electric magnetic field [12]. The value $\omega \tau = 10$ is used for estimation.

The distortion along the $r$-direction in a local volume is:

\[
\Delta r = \frac{1}{1 + (\omega \tau)^2} \times \frac{E_r}{E_z} \Delta z, \tag{5.4}
\]

which is one order of magnitude smaller than the distortion along the $\phi$-direction. And considering that the size of a TPC readout pixel along the $r$-direction is 6 mm, 6 times larger than the size along the $\phi$-direction, the distortion along the $r$-direction is not considered in the paper.

The space charge field is calculated using an analytical method [13]. The value of $E_r/E_z$ with $L = 2$, $k = 5$ and $V_{\text{ion}} = 5$ m s$^{-1}$ is shown in figure 5.

The distortion is larger with the increase of drift length. The hits with maximal drift length have maximal distortion. The maximal distortions as a function of $r$ calculated under different parameters are shown in figure 6. The maximal distortion with $L = 2$, $k = 5$ and $V_{\text{ion}} = 5$ m s$^{-1}$
Figure 5. One-forth view of $E_r/E_z$ in the TPC with $L = 2$, $k = 5$ and $V_{\text{ion}} = 5 \, \text{m s}^{-1}$.

Figure 6. Distortion along $\phi$-direction as a function of electron initial $r$ position with different parameters.

is less than $10 \, \mu\text{m}$. It suggests that the distortion is safety for the CEPC benchmark parameters. However, in the worst scenario with $L = 200$, $k = 100$ and $V_{\text{ion}} = 5 \, \text{m s}^{-1}$, corresponding to the designed luminosity of the FCC-ee with a bad IBF control, the maximal distortion can reach an order of $10^4 \, \mu\text{m}$.

A few approaches can be taken to mitigate the distortion. If the ion back flow can be controlled from $k = 100$ to $k = 5$. Decreasing the TPC length and increasing the magnetic field also help to reduce the distortion.

Moreover, the distortion is along the direction of $\mathbf{E} \times \mathbf{B}$. Given a hit with definite position, the distortion can be corrected back.

The momentum resolution of tracks are mainly determined by the silicon detector placed at the inner most layer of the CEPC conceptual detector, while the TPC is mainly used for track finding. Combining the factors together, TPC is also feasible for the FCC-ee.
6 Conclusion

Using a sample of 9 thousand fully simulated $Z \to q\bar{q}$ events at center of mass energy of 91.2 GeV, we studied the voxel occupancy and the local charge density of the CEPC TPC at Z pole operation for future circular electron positron colliders, with an instant luminosity of $2 \times 10^{34}$ to $2 \times 10^{36}$ cm$^{-2}$ s$^{-1}$.

Given the fact that the beam bunch is evenly distributed along the accelerator circumference, the voxel occupancy is extremely low ($1.4 \times 10^{-4}/1.4 \times 10^{-6}$ for the inner most layer and $3.4 \times 10^{-5}/3.4 \times 10^{-7}$ on average) and poses no pressure for the TPC usage at both CEPC and FCC-ee.

The distortion of the TPC hit positions induced by the ion charges is estimated with dedicated program and calculation. At instant luminosity of $1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, corresponding to the CEPC nominal luminosity, the distortion is negligible. To conclude, the distortion stress no pressure to the CEPC TPC.

At instant luminosity of $1 \times 10^{36}$ cm$^{-2}$ s$^{-1}$, corresponding to the FCC-ee nominal luminosity, and an ion back flow control of percent level, the distortion can be as large as $10^4 \mu$m at the inner most TPC layer at the CEPC conceptual detector geometry, which is two orders of magnitude larger than the intrinsic TPC spatial resolution of 100 $\mu$m.

A few approaches are proposed to reduce the effects caused by distortion:

• Ion back flow control technology; the ion back flow should be controlled to per mille level, in other word, only 1–10 back flow ions is allowed for each primary ionization.

• Dedicated distortion correction algorithm, for the inner most layers, which should result in a mitigation of the hit position distortion by 1 order of magnitude.

• Adequate track finding algorithm that could link the TPC track fragments to vertex tracks at high efficiency and purity.

Taking all of these approaches account, the distortion can be mitigated by approximately 2 orders of magnitude. and if the above items can be achieved, the usage of TPC is also a feasible option at the FCC-ee.

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