Evaluation of hit point distortion due to beamstrahlung in the ILD-TPC using a new 3-d code

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Abstract. The International Large Detector (ILD) is proposed as a detector concept for a future electron-positron Higgs Factory. Its charged particle tracking system is built around a Time Projection Chamber, complemented with internal and external layers of silicon detectors. In this study, we estimate the charge which builds up in the TPC volume due to beamstrahlung backgrounds at ILC and FCC-ee, and the distortions that it induces on the drifting electrons used to measure track trajectories. This talk was presented at the International Workshop on Future Linear Colliders (LCWS 2025) in Valencia, Spain.

Keywords: ILC, FCC-ee, Beam Background · TPC

1 Introduction

The realization of an electron-positron Higgs factory is eagerly anticipated in order to explore physics beyond the Standard Model. The International Linear Collider (ILC)[1] and Future Circular Collider (FCC-ee)[2] are two proposed Higgs factory projects currently under consideration.

The International Large Detector (ILD) concept has been designed to operate at such a Higgs factory[1][2]. It's tracking system is built around a Time Projection Chamber (TPC), which provides quasi-continuous charged particle tracking within a large volume, enables particle identification through precise measurements of the specific energy loss dE/dx, while minimising multiple scattering thanks to its very low material budget.

A key physics requirement for the ILD detector arises from the recoil mass measurement in the Higgs–strahlung process. To achieve the required precision, the full tracking system — including the vertex detector, silicon inner tracker, TPC, and silicon external tracker — should provide a momentum resolution of $dp/p^2 = 2\times10^{-5}$ GeV^{-1}c. At a magnetic field of 3.5 T, the momentum resolution of the TPC alone is expected to be approximately 1×10^{-4} GeV^{-1}c.

Under these conditions, the corresponding sagitta resolution is estimated to be approximately 6 μm, which is essential for meeting the overall ILD tracking performance requirements. This performance is achieved with a single hit point resolution of 60–100 μm in the r–ϕ plane over the full drift length of 2.2 m.

The focus of this study is the distortion caused by positive ions which build up within the TPC volume. Such distortions can affect the sagitta measurement. Previous studies on the effects of ions in the TPC mainly have assumed ϕ symmetry. This symmetry is not respected in reality, due to the flat beam profile, beam crossing angle, and non-symmetric distribution of material in the Machine Detector Interface (MDI). In this study, we extend the analysis to a full three-dimensional treatment, and also estimate the variability of distortions.

2 Ion Backgrounds in the ILD TPC

Several background sources have the potential to negatively affect the TPC performance, among which beamstrahlung is expected to be one of the most important. Beamstrahlung originates from beam–beam interactions at the interaction point, where the strong electromagnetic fields within and around the colliding beam bunches result in the production of large numbers of photons, electrons and positrons with low transverse momentum (p_T) .

Interactions of these beamstrahlung-induced particles with materials in the Machine-Detector Interface (MDI) can generate photons which may enter the TPC volume. Such photons can liberate electrons from atoms in the TPC gas, which, constrained by the detector's magnetic field, produce characteristic "microcurlers" as they move through the TPC, losing energy by ionisation. Ions produced directly in the TPC gas are referred to as primary ions.

Ionisation electrons drift along the E-field to the TPC readout plane, where they are gas-amplified (by e.g. a GEM or Micromegas device). Ions produced during this amplification process may subsequently enter the main TPC volume, providing an additional source of ions. Various techniques can be used to reduce this ion back flow, for example an ion gate (which can be used at ILC, but not at FCC-ee, due to the beam bunch structure) or multiple GEM layers. Those amplification ions which do enter the TPC volume are called secondary ions. At ILC, the use of a gating device will suppress the vast majority of secondary ions, so the effect of primary ions is expected to be dominant. At FCC-ee, we expect ion blocking to be significantly less effective, so the secondary ion contribution will be more important.

The ion drift speed in the T2K gas proposed for the ILD-TPC is assumed to be 5×10^3 mm/s. Given the 2.2 m half-length of ILD's TPC, ions produced during the previous 0.44 s may be present in the TPC volume. At ILC with 5 Hz operation this corresponds to up to three bunch trains, each containing 1312 bunches, while at FCC-ee- 91 it corresponds to about 16 M bunch crossings. These ions distort the electric field and the trajectory of drifting electrons. Distortions in the ϕ direction, which directly affect tracks' sagitta measurement, are caused by the radial electric field component E_r through the $\mathbf{E} \times \mathbf{B}$ effect.

3 Simulation WorkFlow

Samples of beamstrahlung at ILC-250 and FCC-ee-91 were produced by the GuineaPig program. These were then passed through a DD4hep/Geant4- based simulation of the ILD detector: ILD_l5_v03 for the ILC, and ILD_FCC-ee_v01 for the FCC-ee [4]. The hits simulated in the TPC gas were used to estimate the three-dimensional distribution of ions within the TPC volume, with a simple modeling the ion drift towards the cathode.

Next, the electric field distortion caused by the resulting charge distribution was calculated, assuming a cylindrical TPC with conducting walls and central membrane. The electric field distortion was obtained by solving the three-dimensional Poisson equation using a Green's function method [5].

The solution, which involves sums of modified Bessel functions, was expanded in the z and ϕ directions and truncated at finite maximum orders, denoted as $n_{\max}$ and $m_{\max}$. To determine appropriate truncation orders, the calculation was repeated while increasing $n_{\max}$ and $m_{\max}$, and the convergence of the resulting electric field distortion was examined. It was found that beyond a certain truncation order, further increases had a negligible effect on the distortion. Based on this convergence study, the truncation orders $(n_{\max}, m_{\max}) = (50, 50)$ were adopted in the present analysis. Finally, the distortion in the azimuthal direction, $r\Delta\phi$, of an electron drifting through the TPC was evaluated using the Langevin equation, for various different starting positions.

4 Results

4.1 Ion distribution

Figure 1 shows a 3d view of the simulated ion distribution at the ILC-250, and the dependence of the ion density on radius. A higher ion density is observed at small radius, reflecting the larger number of background particles produced at smaller radii. These ion distributions are used as input to the subsequent two-dimensional and three-dimensional analyses.

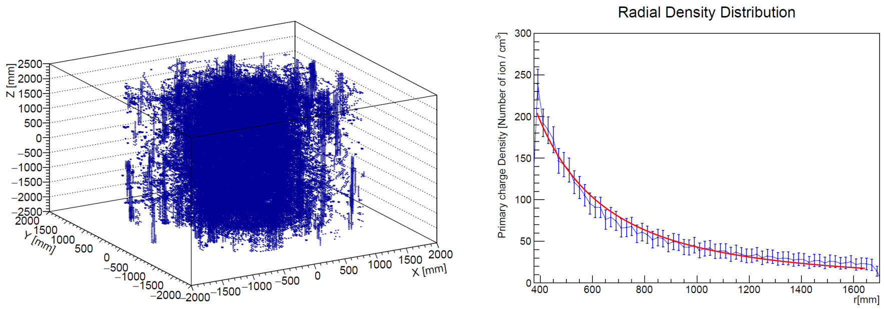
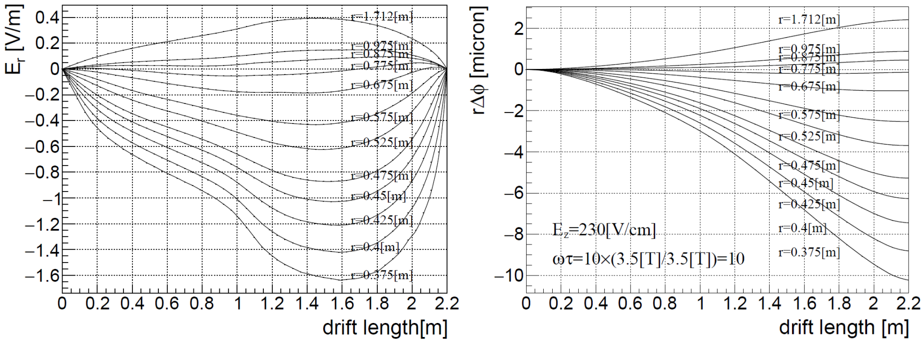


Fig. 1. Left : distribution of primary ion at ILC-250 in 3-d, Right : primary ion density as a function of radius r.

4.2 Two-dimensional distributions of the radial electric field and space-charge distortion

The effects caused by primary ions accumulated from three bunch trains at ILC-250 were investigated. Figure 2 shows the radial electric field E_r induced by the ion charge distribution as a function of r and z, and the distortion in the ϕ direction experienced by an electron drifting through the field, $r\Delta\phi$. The radial electric field E_r becomes zero at the conducting cathode and anode planes. The lowest curve corresponds to the innermost radius, while curves at higher positions correspond to regions closer to the outer radius. The distortion is largest (and negative) at the inner radius, and becomes positive towards the outer surface of the TPC. There is a region, at radius around 0.8 m, in which the distortion is rather small.

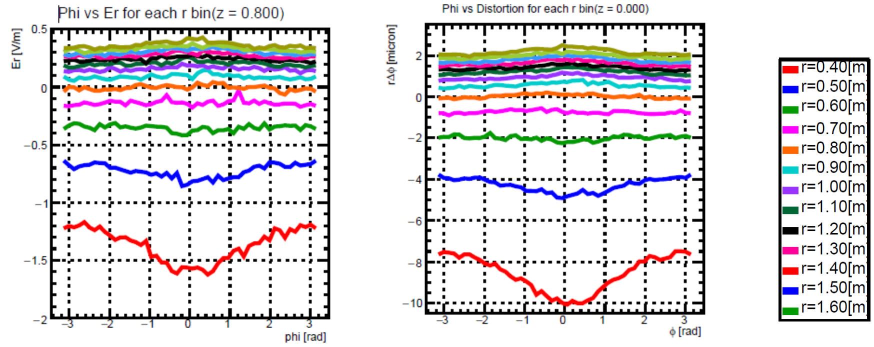


E_r $r\Delta\phi$

Fig. 2. Radial electric field distortion (left) and deviation in the ϕ - direction of electron arrival position (right) calculated at different positions within the TPC at ILC-250, assuming a ϕ - symmetric charge distribution.

4.3 Three-dimensional distributions of the radial electric field and space-charge distortion

We here extend the study at ILC-250 to a full three-dimensional analysis, taking the ϕ - dependence into account. Figure 3 shows the ϕ-dependent variation of the radial electric field E_r, and distortion $r\Delta\phi$. The radial electric field distortion reaches up to approximately -1.6 V/m, and the corresponding $r\Delta\phi$ is around -10 μm. As seen for $r = 0.4$ m (red line), smaller radii experience larger distortions. Clear ϕ-dependent variations, which were ignored in the two-dimensional analysis, are observed. The distortion $r\Delta\phi$ is not uniform with ϕ, with a maximum variation of approximately 0.9 μm (RMS).



E_r $r\Delta\phi$

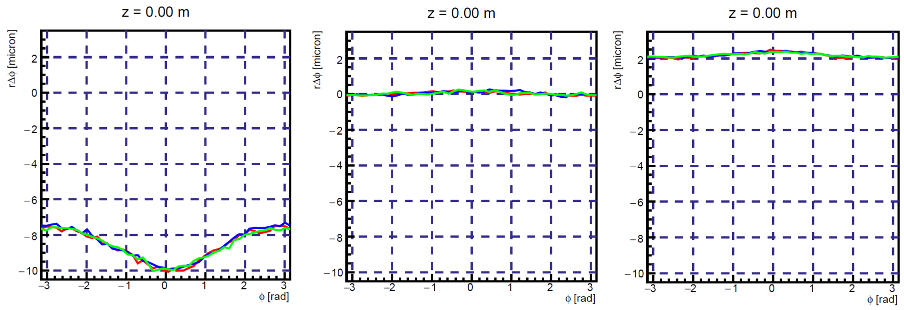
Fig. 3. The radial electric field distortion E_r (left, at z = 0.8 m) and the deviation in the electron arrival position (right, for an electron starting at z=0) at different radii r and ϕ, due to beamstrahlung at ILC-250.

4.4 Variability of distortions

There are two main aspects of the time stability of distortions: the variation during a bunch train, as the ion cloud builds up with successive bunch crossings, and the reproducibility of the distortion at a given point within different bunch trains. We here address the second aspect, while the first will be addressed in future work.

Three independent input data sets of ILC-250 beamstrahlung simulation were used to construct three statistically independent ion distributions. The resulting $r\Delta\phi$ distortions were compared. Figure 4 shows the $r\Delta\phi$ distortions caused by the ion distributions for the full drift length at three radii in the TPC. The three curves representing the different samples almost overlap, indicating that the time dependence is much smaller than the r and ϕ dependence.

To quantify the difference, we calculate the RMS difference between the data sets; at $r = 0.4$ m, where the maximum distortion occurs, the RMS difference is approximately 0.04 μm. For an electron drifting near the TPC center at $R = 0.8$ m, the RMS is about 0.01 μm.



$r = 0.4\,\mathrm{m}$ $r = 0.8\,\mathrm{m}$ $r = 1.6\,\mathrm{m}$

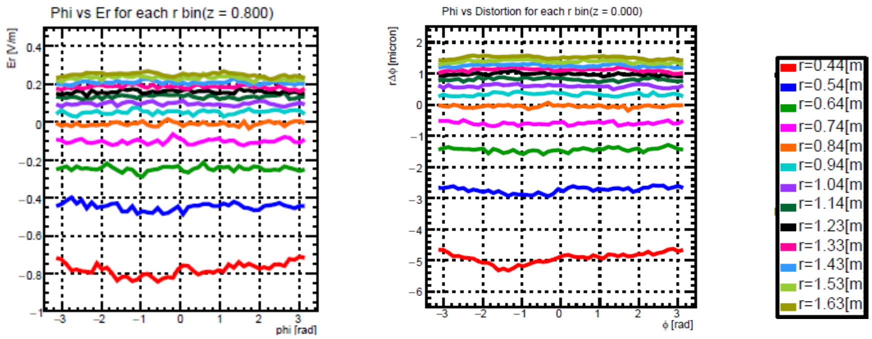
Fig. 4. Comparison of ϕ-dependent distortions $r\Delta\phi$ calculated for three independent ILC-250 data sets(red, blue, and green), for full drift length at different radii r.

4.5 Distortions from beamstrahlung at FCC-ee

FCC-ee presents a number of additional challenges compared to ILC, related to the collision rate and bunch structure. The high collision rate implies that the TPC, with its slow ion drift, integrates many bunch crossings. The continuous rather than pulsed arrival of collisions means that the use of an active gating device is not possible. Therefore, in addition to primary ions, the effects of secondary ions were also investigated.

For Z-pole operation at FCC-ee, the maximum ion drift time within the TPC (0.44 s) corresponds to around 16 M bunch crossings. The available statistics of beamstrahlung simulations is only 4000, so the analysis was performed assuming 4000 bunches arriving over 0.44 s. The final results are then scaled to the full luminosity. Similar to the ILC 250 GeV case, a three-dimensional ion distribution was constructed using simulation data describing the behavior of beamstrahlung background events in the ILD detector where FCC-ee's MDI was incorporated. Based on this ion distribution, the electric field distortion was evaluated and the resulting distortion $r\Delta\phi$ was calculated.

The results for primary ions are shown in Fig. 5. The maximum radial electric field distortion due to primary ions reaches -0.9 V/m, and the maximum distortion $r\Delta\phi$ around -5.5 μm. The larger distortions are again at smaller radii. The ϕ - dependence is significantly smaller than that seen at ILC. To scale to the full luminosity at FCC-ee-91 we scale the above numbers by a factor $16 \times 10^6 / 4 \times 10^3 = 4000$, giving a maximum distortion in $r\Delta\phi$ of around 22 mm.

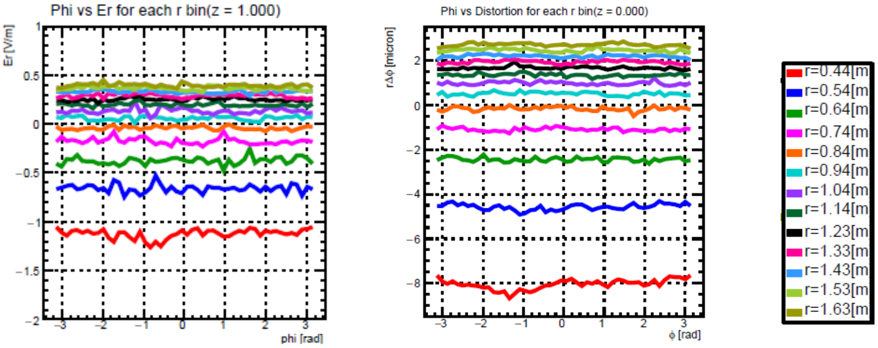


E_r $r\varDelta\phi$

Fig. 5. Primary ions at FCC-ee-91, assuming 4000 bunch crossings in 0.44s. The left figure shows E_r (z= 0.8 m, at the point of maximum electric field distortion) at positions with different radii and azimuthal angle ϕ, while the right shows $r\varDelta\phi$ for maximum drift length: an electron drifting 2.2 m from the central cathode to the readout plane.

Corresponding results for secondary ions are shown in Fig. 6. We here assume that one electron entering the gas multiplier results in one secondary ion entering the TPC volume. For different levels of ion feedback, these results can be simply scaled. The radial electric field distortion reaches -1.3 V/m, and the corresponding $r\varDelta\phi$ is estimated to be around -9 μm. Scaling to the full FCC-ee-91 luminosity, we estimate a maximum distortion of around 36 mm, assuming an ion feedback factor of unity.

The variability of this distortion was evaluated by comparing the results obtained using two independent input data sets, each consisting of 2000 bunch crossings. The resulting variation in distortion was found to be below the 1% level. This variation is caused by statistical difference between these two datasets, and is expected to become much smaller when scaled to the actual FCC-ee bunch rate.



E_r

$r\Delta\phi$

Fig. 6. Secondary ions at FCC-ee-91, assuming 4000 bunch crossings in 0.44s. The left figure shows E_r (z= 1.0 m, at the point of maximum electric field distortion), while the right shows $r\Delta\phi$ for maximum electron drift length.

5 Conclusion

The distortion $r\Delta\phi$ due to ions in the TPC was calculated in three dimensions for primary ions originating from beamstrahlung at ILC and FCC-ee.

As a result, the maximum distortion is approximately 10 μm for three ILC bunch trains accumulated in the TPC. A significant ϕ - dependence was observed, so the ϕ - dependent correction utilizing the new 3d code is feasible and useful. The scale of time variations near the center of TPC is about 0.1 μm (RMS) at ILC, much smaller than the required sagitta resolution of the TPC. Thus, no time-dependent correction is required, assuming stable accelerator conditions.

In addition, the effects of ions generated by beamstrahlung at the FCC-ee were evaluated separately for primary and secondary ions. The expected maximum distortions at full FCC-ee luminosity are approximately 20 mm and 36 mm for primary and secondary ions, respectively, assuming an ion feedback factor of unity. We note that in each scenario the region of the TPC at intermediate radii experiences distortions much smaller than the maxima reported above. The statistical time variability was also estimated, and is expected to be very small. Therefore, no time-dependent correction is considered necessary, assuming stable running conditions.

Acknowledgments

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