# TPC distortion study at future electron-position colliders

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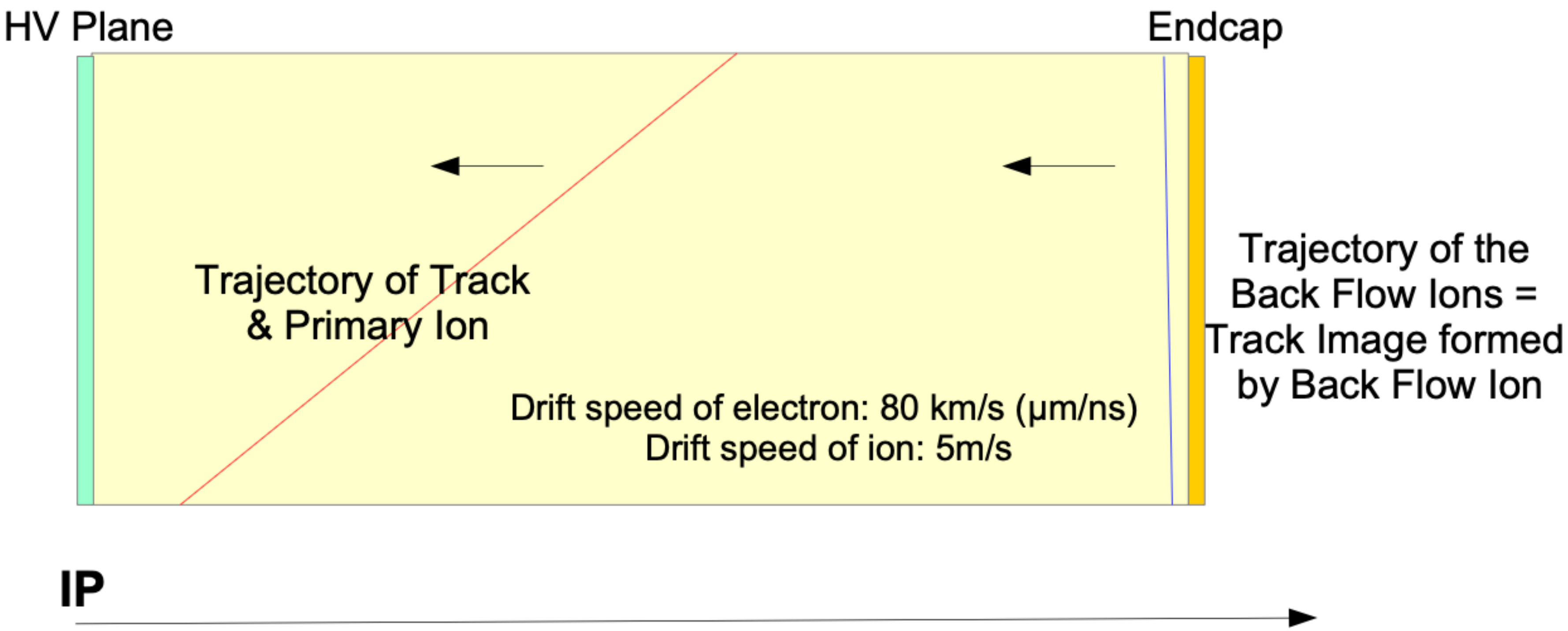
24 Oct, 2023

International Workshop on the High Energy Circular Electron-Position Collider

# TPC at Z factories

- A promising technology for the future electron positron colliders
  - High efficiency
  - High Precision
  - Low Material Budget
  - dEdx
- Challenges
  - Occupancy [√] [2017 JINST 12 P07005]
  - Space Charge Distortion [ ? ]
  - Beam induced background [ ? ]
  - dE/dx measurements [√] [EPJC 2018 78:464][ArXiv: 2209.14486]

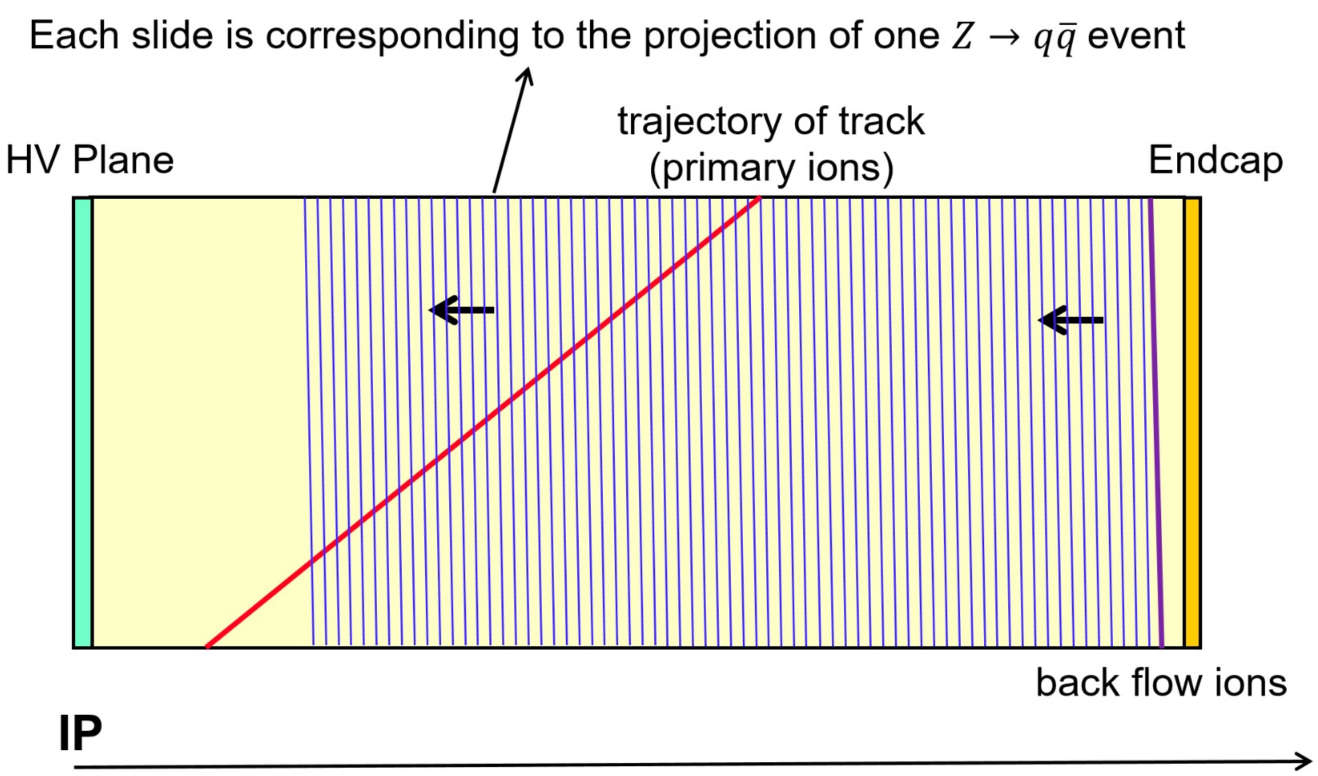
# How TPC works




- Ion Charge ~ Primary + Back flow ion ~ (1 + k), k = Gain * IBF
- Time scale for electron/ion drifting: 30 micro-sec/0.5 sec

# At Z-pole with Lumi = $2 \times 10^{36}$ cm$^{-2}$ s$^{-2}$

- Electron drift time scale: 30 μs:
  - 30 μs*60 kHz ~ 2 events drifting in the same time, a bit challenge for the reconstruction
- Ion drift time: ~ 0.5 second (from the Endcap to the HV plane)
  - 60000 Ion Disks: 30000 at each half TPC, quite significant charge in the gaseous volume...




Need to investigate the effects of ion electric fields on TPC resolution

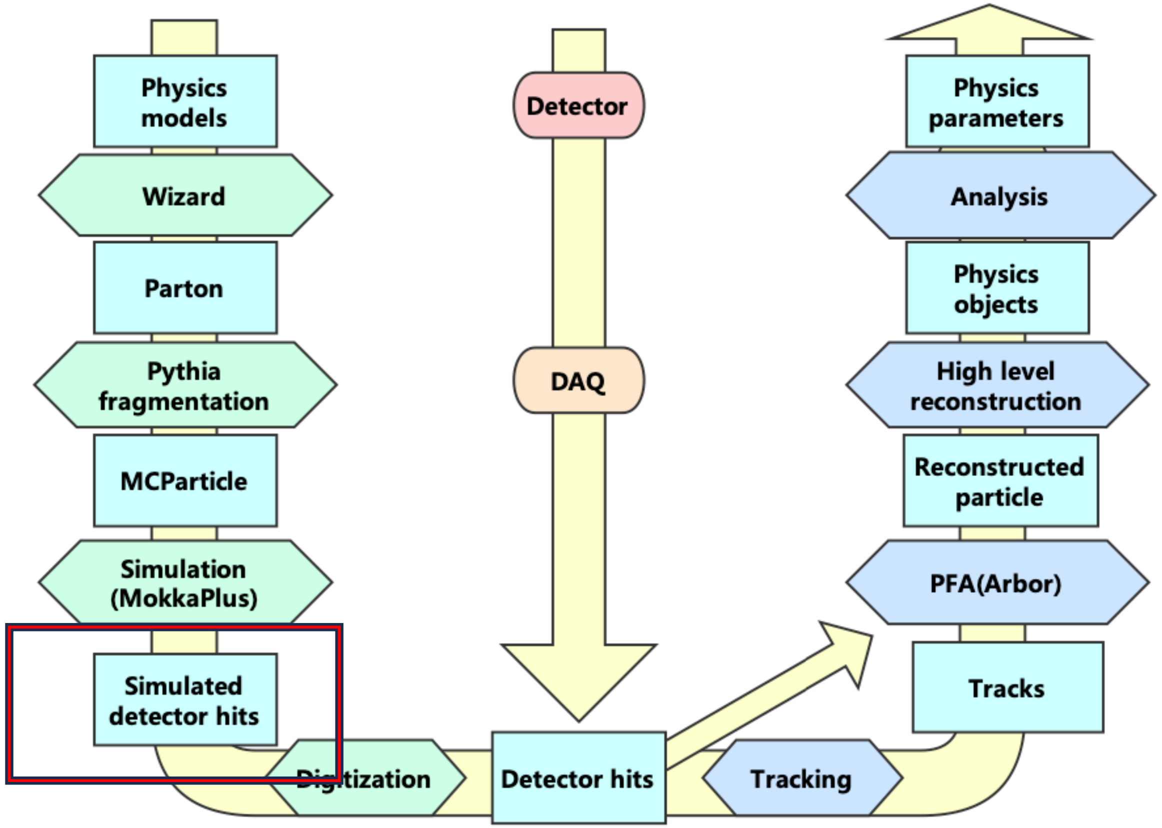
# Method

- Step1: Calculate the ion charge density
  - Simulation
- Step2: Calculate the electric field
  - Green function
- Step3: Calculate the distortion

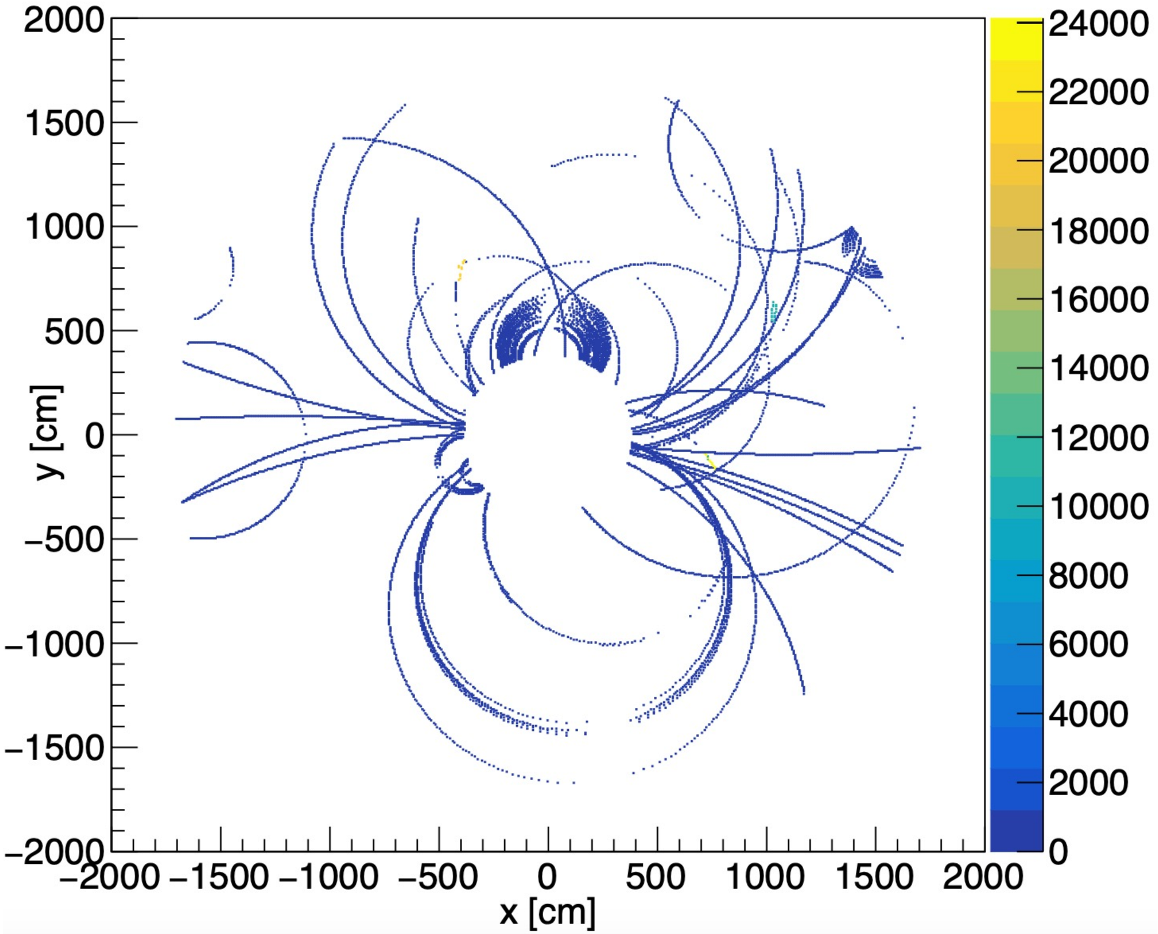
$$\boxed{\left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)}\frac{\boldsymbol{E}_{\perp i}\times\hat{\boldsymbol{B}}}{E_0}\Bigg]$$

# Step1: Calculate the ion charge distribution

- Sample: 9 thousand Z → qq events
- Generate ions alone the trajectory of the tracks: 9.4 ions / mm

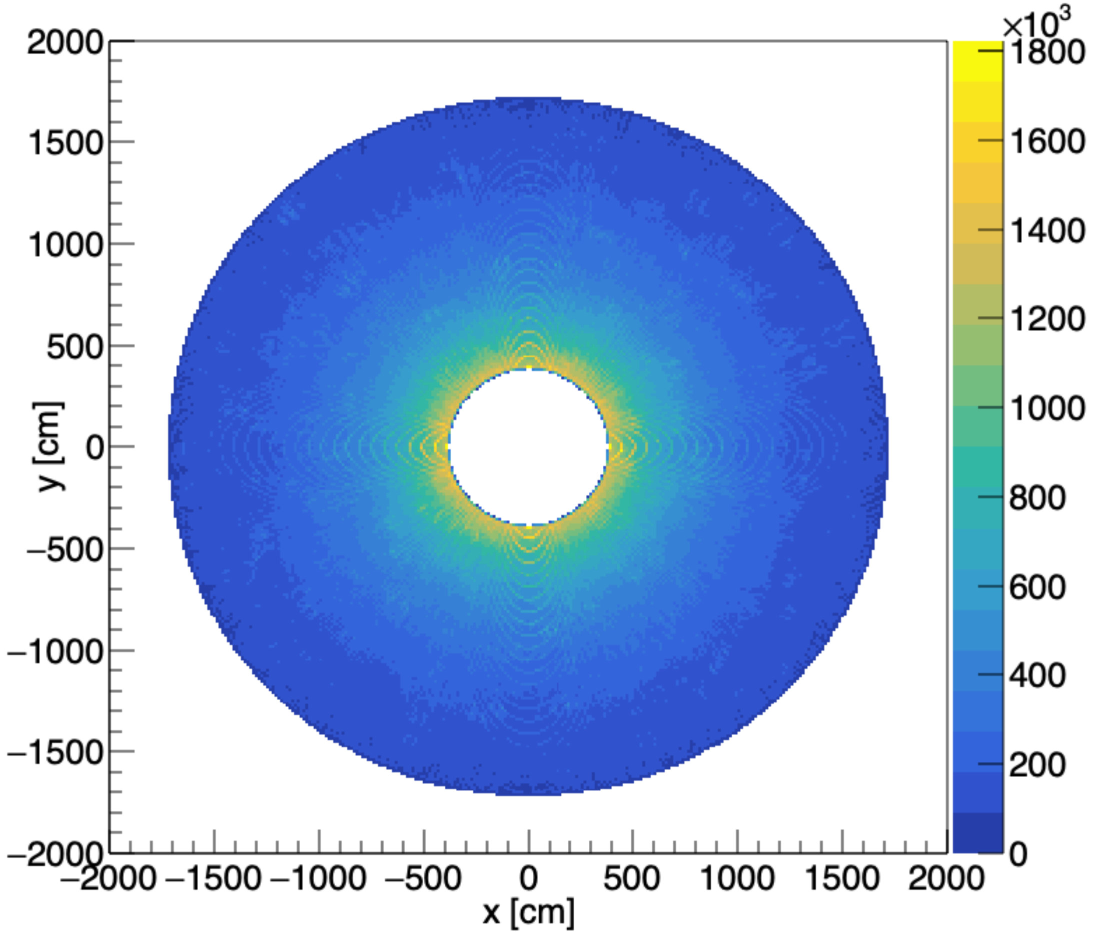


# Charge density profile




**1 event**

**Arbitrary normalized**




**Multiple events**

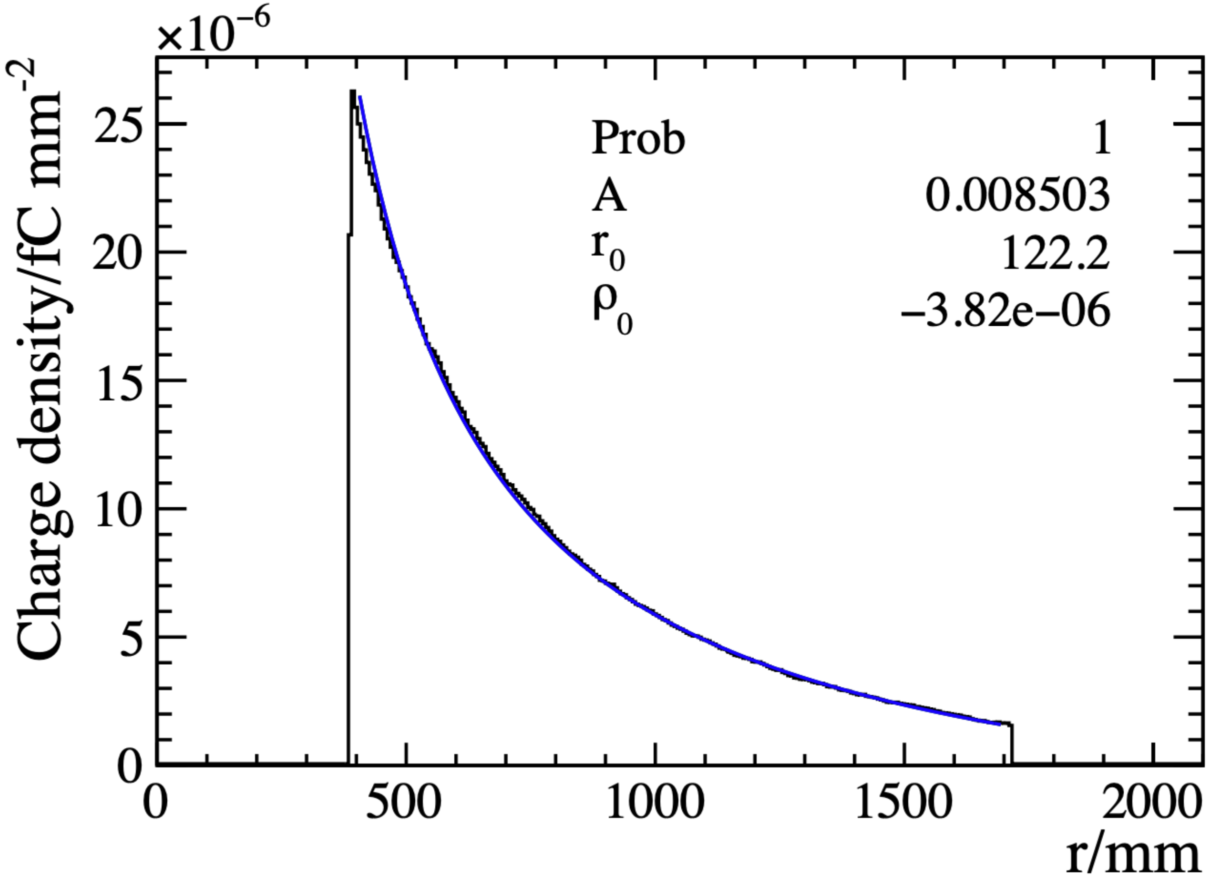
# Charge density profile

- Charge density is independent of azimuthal angle and z
- Parameterize:

$$(1+k)\frac{L}{V_{\text{ion}}} \times \rho \times R$$

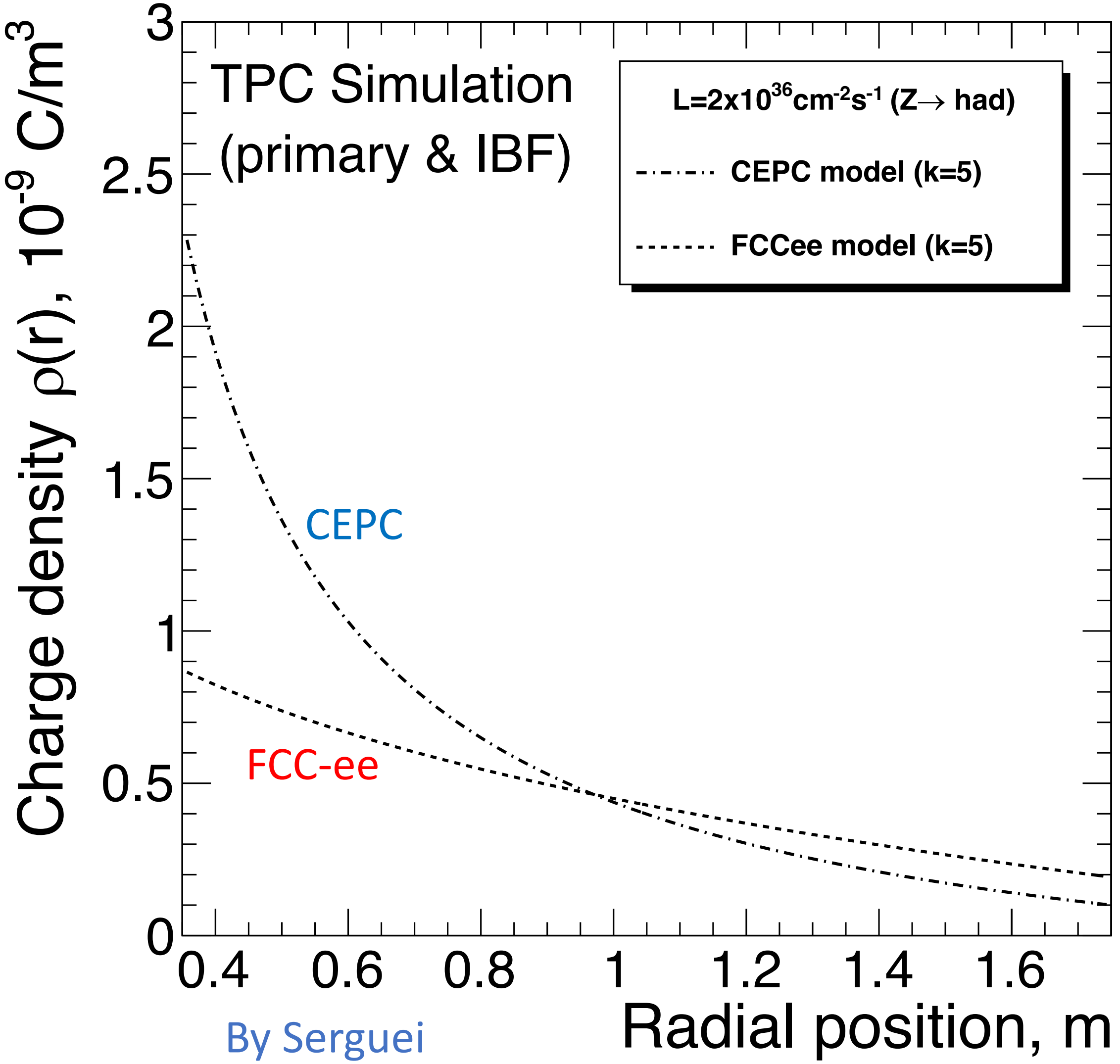
$$\rho = \frac{9.135 \times 10^{-3}}{r/\,\text{mm} - 97.87} - 4.166 \times 10^{-6}\ [\,\text{fC mm}^{-2}]$$

  - Lumi = L * 10^**34**
  - k: back flow ions
  - R: 300 Hz



# A different modeling by Serguei for FCC-ee study

- Hit density is estimated with the average charged track length in the TPC volume.
- Overall density are similar, the line shape are different




By Serguei

# Step2: Calculate the electric field

$$\triangle\phi_0(\boldsymbol{x}) = 0$$
$$\triangle\phi_{\rm ion}(\boldsymbol{x}) = -4\pi\,\rho_{\rm ion}(\boldsymbol{x}) \qquad \text{in } \boldsymbol{x}\in D$$

$$\phi(\boldsymbol{x}) = \phi_0(\boldsymbol{x}) + \phi_{\rm ion}(\boldsymbol{x})$$
$$\longrightarrow \quad \boldsymbol{E} = \boldsymbol{E}_0 + \boldsymbol{E}_{\rm ion} = \boldsymbol{E}_0 - \nabla\phi_{\rm ion}(\boldsymbol{x})$$

All we need is Green's function for

$$\boxed{\triangle G(\boldsymbol{x},\boldsymbol{x}') = -4\pi\delta(\boldsymbol{x}-\boldsymbol{x}')}$$

E-field distortion is then given by superposition:

$$\boxed{\phi_{\rm ion}(\boldsymbol{x}) = \int_D d^3\boldsymbol{x}\, G(\boldsymbol{x},\boldsymbol{x}')\,\rho_{\rm ion}(\boldsymbol{x}')}$$

Boundary Conditions

$$\boxed{\phi_0(\boldsymbol{x}) = V_i \quad \boldsymbol{x}\in C_i}$$

$$\boxed{\phi_{\rm ion}(\boldsymbol{x}) = 0 \quad \boldsymbol{x}\in\partial D}$$

$$\boxed{G(\boldsymbol{x},\boldsymbol{x}') = 0 \quad \boldsymbol{x}\in\partial D}$$

$$E_r(r,z) = -8\pi\sum_{n=1}^{\boxed{\infty}}\frac{\sin(\beta_n z)}{I_0(\beta_n a)K_0(\beta_n b)-I_0(\beta_n b)K_0(\beta_n a)}$$
$$\Bigg[[K_0(\beta_n b)I_1(\beta r)+I_0(\beta_n b)K_1(\beta_n r)]\int_a^r dr'\,\frac{K_0(\beta_n a)I_0(\beta r')-I_0(\beta_n a)K_0(\beta_n r')}{K_0(\beta_n r')I_1(\beta_n r')+K_1(\beta_n r')I_0(\beta_n r')}$$
$$\boxed{\int_0^L\frac{dz'}{L}\,\sin(\beta_n z')\rho_{ion}(r',z')}$$
$$+[K_0(\beta_n a)I_1(\beta r)+I_0(\beta_n a)K_1(\beta_n r)]\int_r^b dr'\,\frac{K_0(\beta_n b)I_0(\beta r')-I_0(\beta_n b)K_0(\beta_n r')}{K_0(\beta_n r')I_1(\beta_n r')+K_1(\beta_n r')I_0(\beta_n r')}$$
$$\boxed{\int_0^L\frac{dz'}{L}\,\sin(\beta_n z')\rho_{ion}(r',z')}\Bigg]$$

z'-integral now inside r'-integral

Possion equation

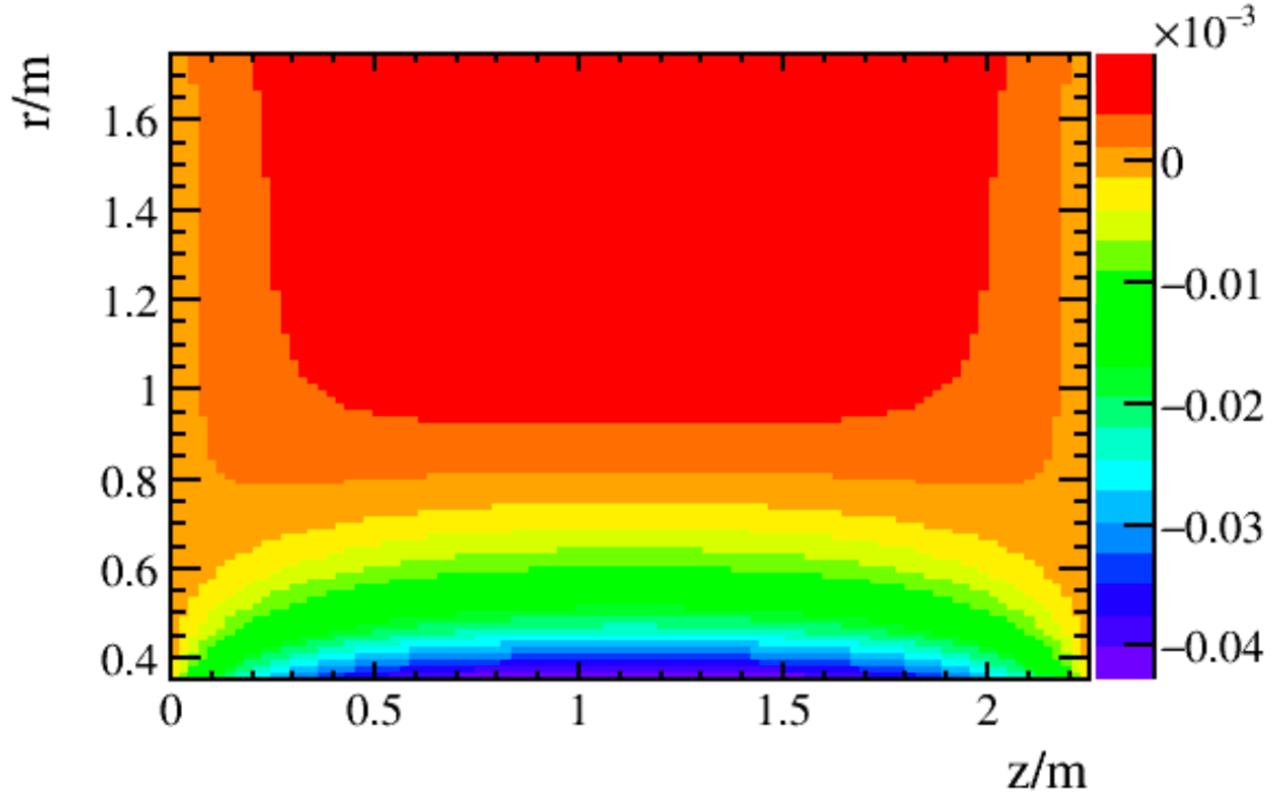
Green function

Electric field is expressed in analytic form

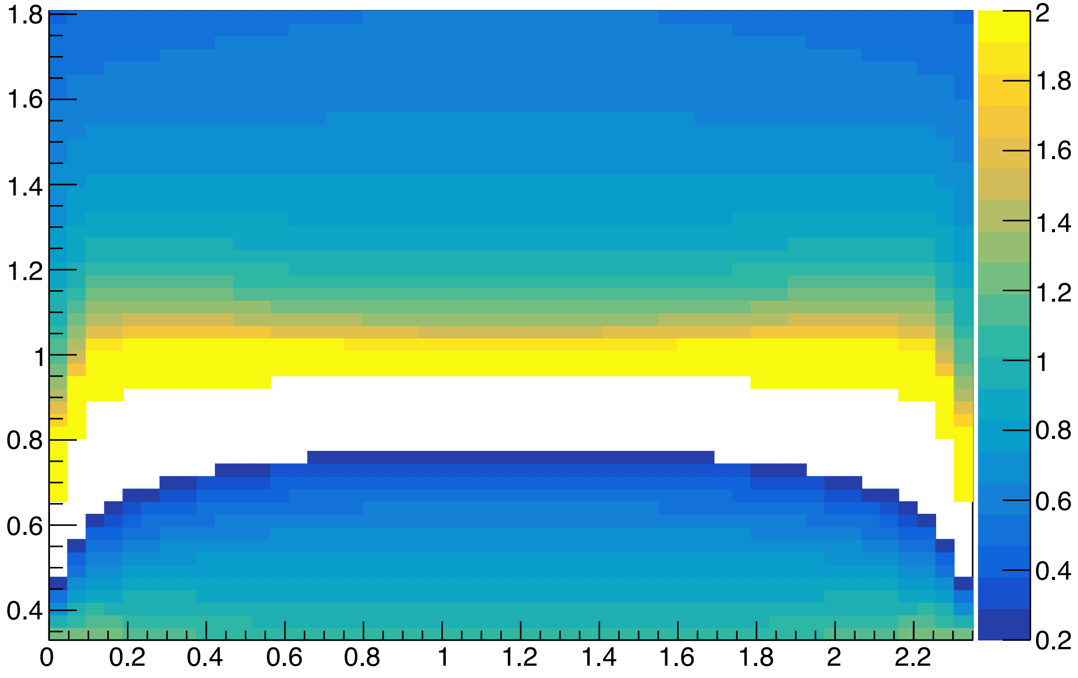
Slide from Keisuke Fujii

# Electric field profile

- Er/Ez




Comparison of different modeling:
Ratio: CEPC modeling/FCC-ee modeling




Difference comes from the ion distribution modeling rather than the detector

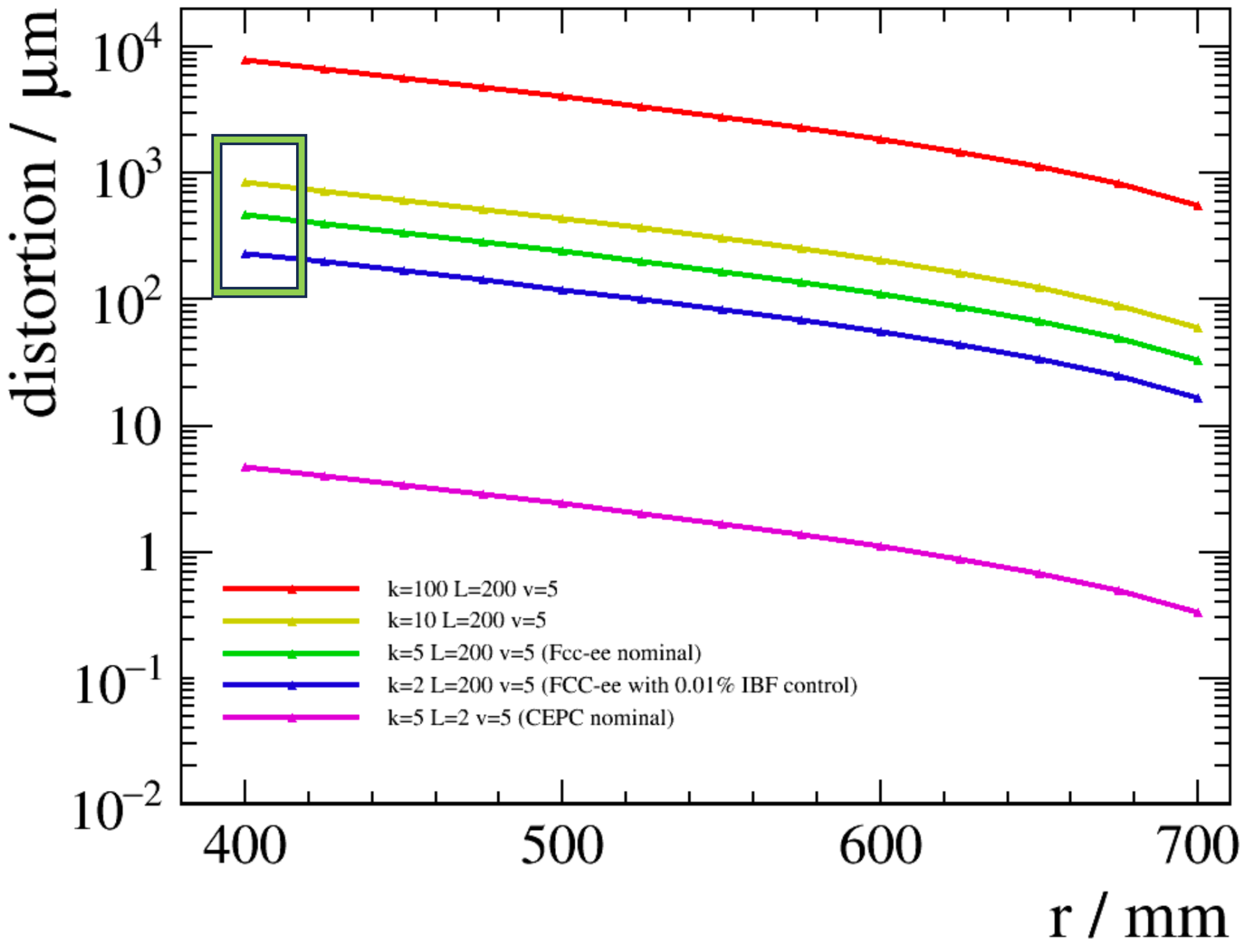
# Step3: Calculate the distortion

- Distortion is calculated by accumulating the distortion at small distance/time.

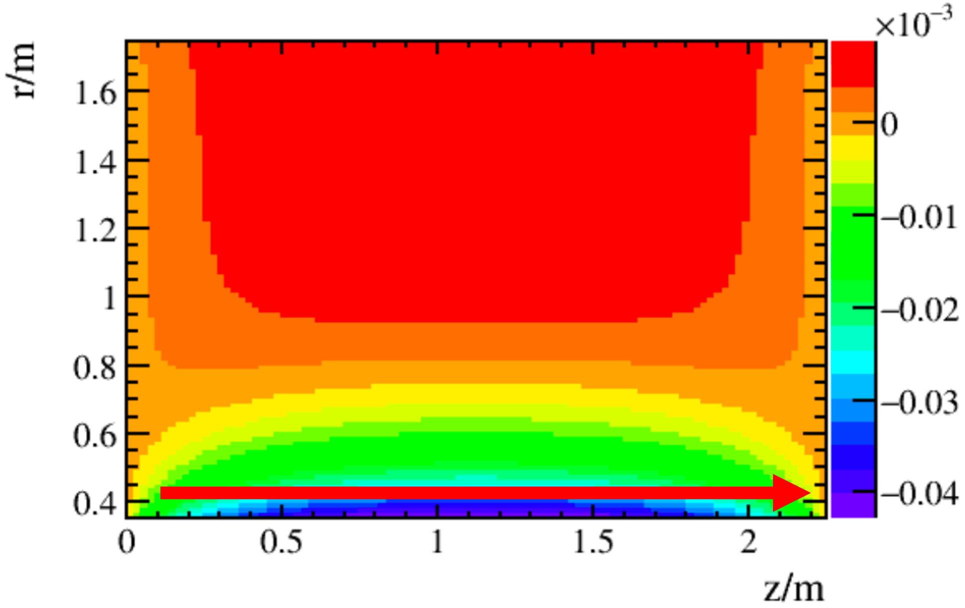
$$
\begin{aligned}
\langle \Delta \boldsymbol{x} \rangle &= \sum_{i=1}^{\boxed{n}} \frac{\Delta \langle \boldsymbol{v} \rangle_i}{\langle v_\parallel \rangle_i} \delta l_i \\
&\simeq \sum_{i=1}^{\boxed{n}} \delta l_i \left[ -\frac{\Delta \boldsymbol{E}_{\parallel i}}{E_0} - \left(\frac{1}{1+(\omega\tau)^2}\right)\frac{\boldsymbol{E}_{\perp i}}{E_0} + \boxed{\left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)} \frac{\boldsymbol{E}_{\perp i}\times\hat{\boldsymbol{B}}}{E_0}\right]
\end{aligned}
$$

- Distortion is linear w.r.t. E-field distortion, and hence also w.r.t. space charge for a drift from the same z to the anode

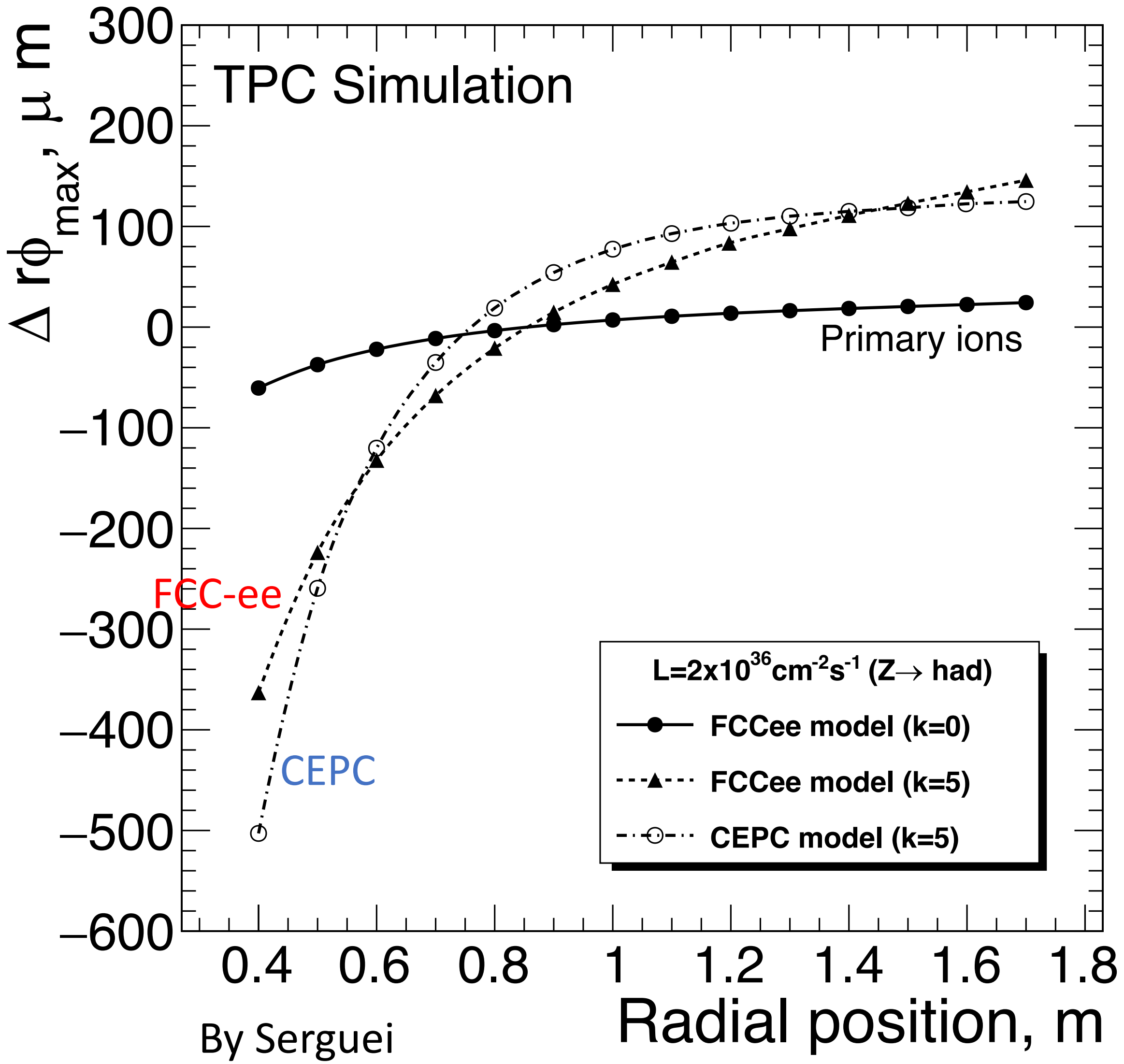
# Maximum distortion




- Maximum distortion as a function of r.
  - At Lumi = $2 \times 10^{36}$ $cm^{-2}$ $s^{-2}$, Backflow k=5
  - Max Distortion ~ 500 µm



# Maximum distortion with FCC-ee modeling




By Serguei

- Consistent results from different modeling.

# Control the distortion

- TPC has a maximal distortion of 0.5 mm at L = 200 (at IBF*k = 5).

| Mitigating options | Reduction factor |
|---|---|
| – Large HV (20 kV -> 40 kV ?) | 4 |
| – Large Ion Mobility (5m/s -> 10m/s) | 2 - 3 |
| – Shorter TPC Length (2.3 -> 2.0) | 1.5 |
| – Larger TPC inner Radius (400 -> 600) | ~ 5 |
| – Increasing B Field | 1.2 |

– Combination of these options reduces the distortions up to 2 orders of magnitude

# Calibration is possible!

- Distortion is **predictable**, what matters is only its fluctuation. Correction is necessary & possible – and we need to understand how well it can be.
- Need to calculate the re-distribution of ions.
- External message, for example, hit in silicon devices, are helpful.
- Hardware based calibration.
- New calibration technique, eg. DNN based calibration [EPJ Web of Conferences 251, 03020 (2021) ].

# Conclusion

- At Lumi = 2 × $10^{36}$ $cm^{-2}$ $s^{-2}$, Backflow k=5, Max Distortion ~ 500 μm, roughly **1 order of magnitude** larger than the intrinsic resolution of TPC.
- Combination of the distortion control technique is possible to lower the distortion by **2 order of magnitude**.

- **Beam induced background** could have large effects on TPC. [under investigation]
- Better understanding of the distortion is required: need a better understanding of the space charge **fluctuation** to develop the calibration algorithm.

- TPC is still **a promising** technology for the future electron positron colliders with **no insurmountable difficulties** working at Z-pole.

# Thanks for your attention

- Thanks Manqi, Keisuke and Serguei for the their help and the material taken from them.