Simulation and prototyping of Pixelated readout TPC for CEPC

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On behalf of CEPC TPC study group

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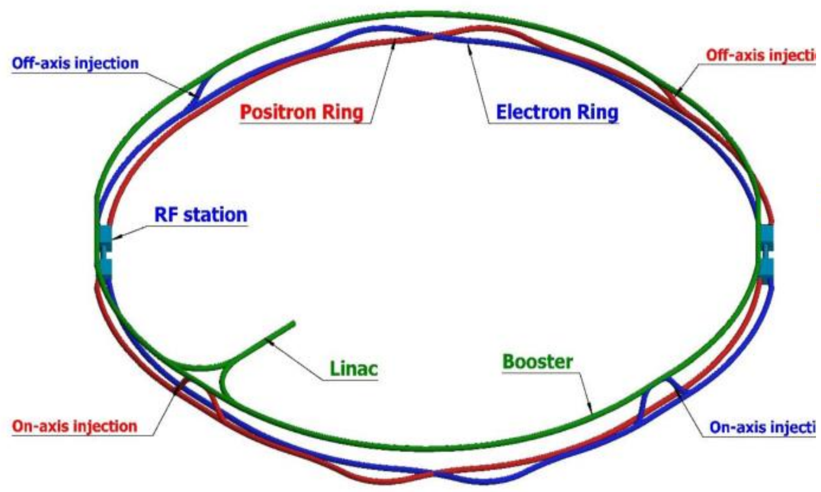
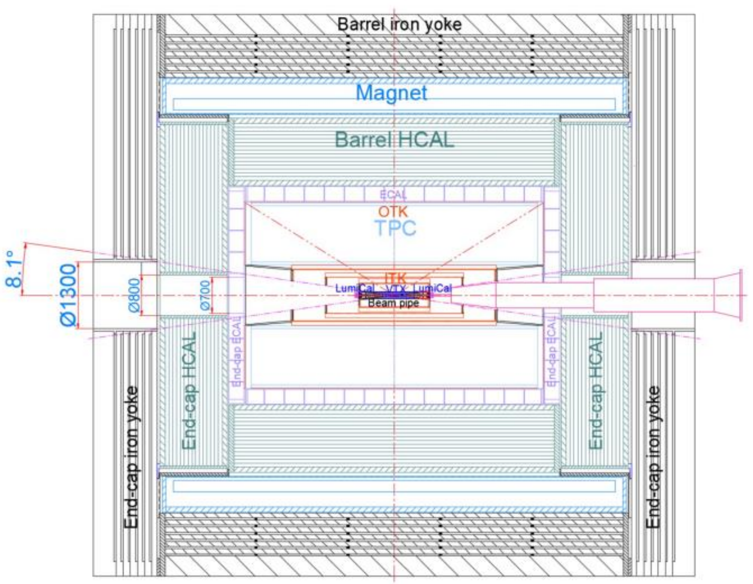
Content

- Motivation: TPC detector for future e+e- collider
- Simulation of beam-induced background in TPC
- Progress on pixelated readout TPC prototype
- Summary

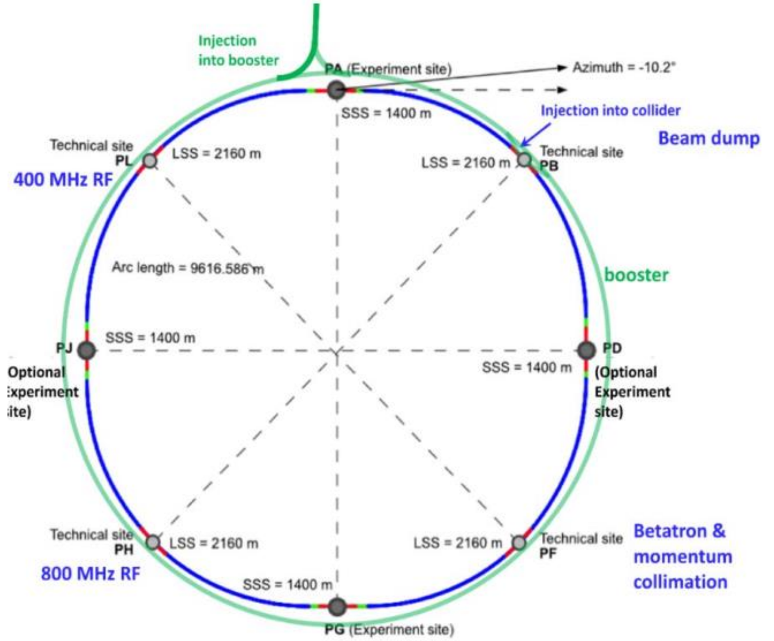
TPC detector for future e+e- collider

- A TPC is a promising main tracking detector candidate for future e+e- colliders experiments
  - Baseline detector in CEPC CDR and ILD
  - **Pixelated TPC** is the baseline main track detector (MTK) in CEPC Ref-TDR
- Pixelated readout TPC is potential to **improve PID requirements of Flavor Physics** at e+e- collider.
- TPC technology can be interest for other future colliders (EIC, KEKb…)





Circular Electron Positron Collider (CEPC)



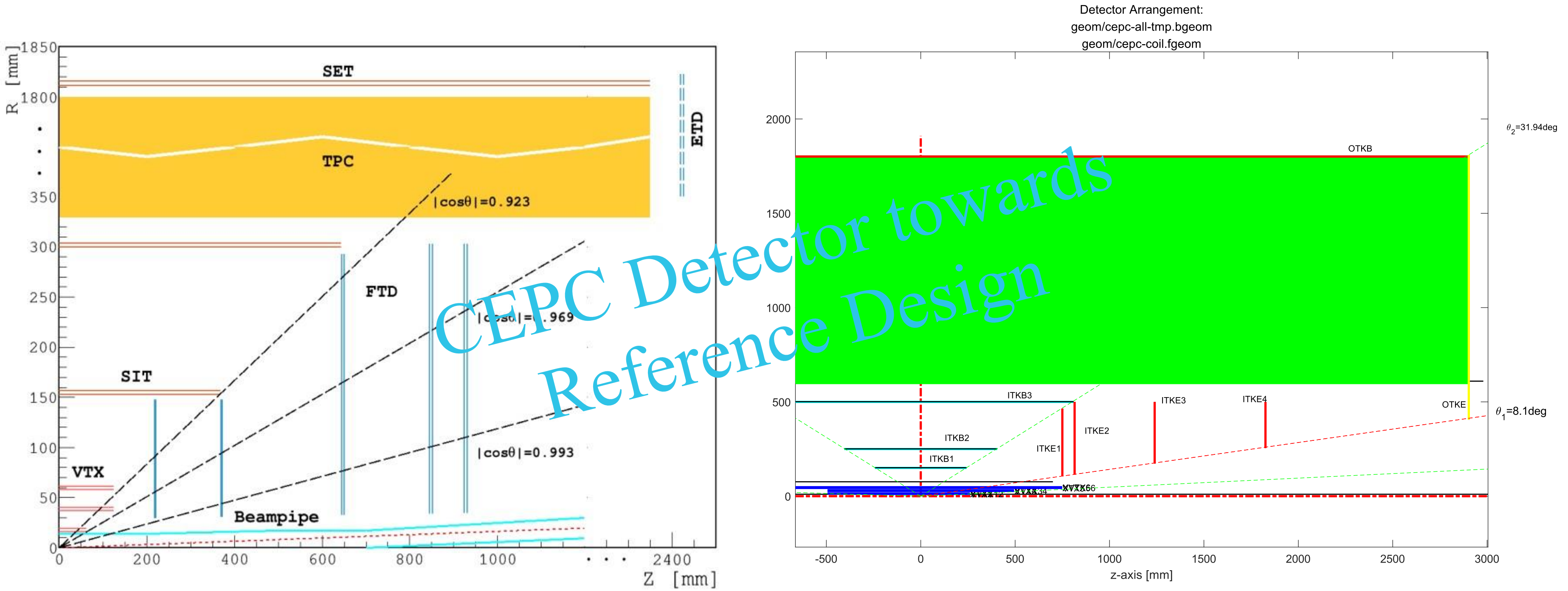
Future Circular Collider (FCCee)

https://arxiv.org/abs/1811.10545

https://arxiv.org/abs/2203.08310

TPC challenges at Higgs/Z

- CEPC operation stages in TDR: 10-years Higgs → 2-years Z-pole → 1-year W
- TPC's inner radius and half length increase to 60cm/290cm in CEPC Ref-TDR
- Challenges:
  - Hit density and Voxel Occupancy
  - Beam induced background
  - Space Charge effect and Distortion
  - …

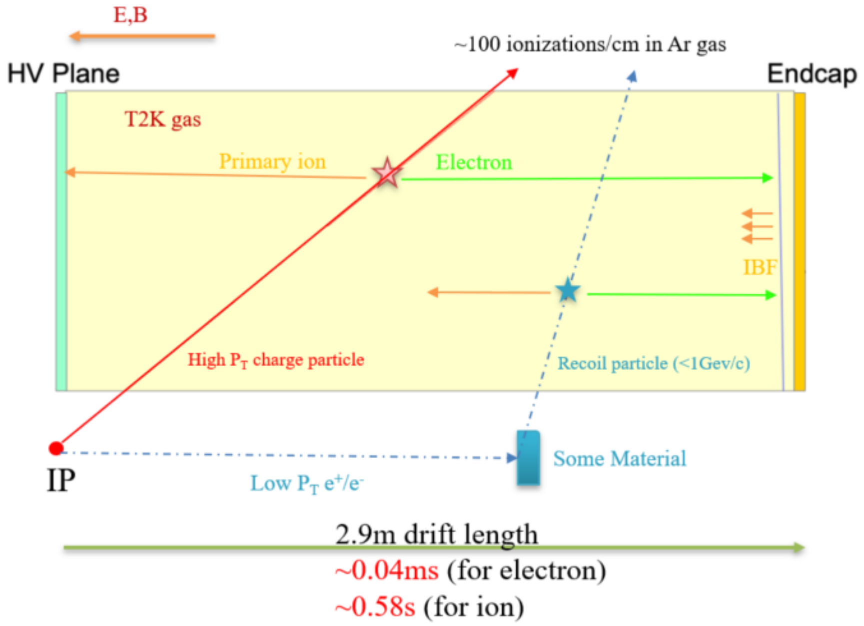


CEPC TPC layout in CDR(left) and ref-TDR(right)

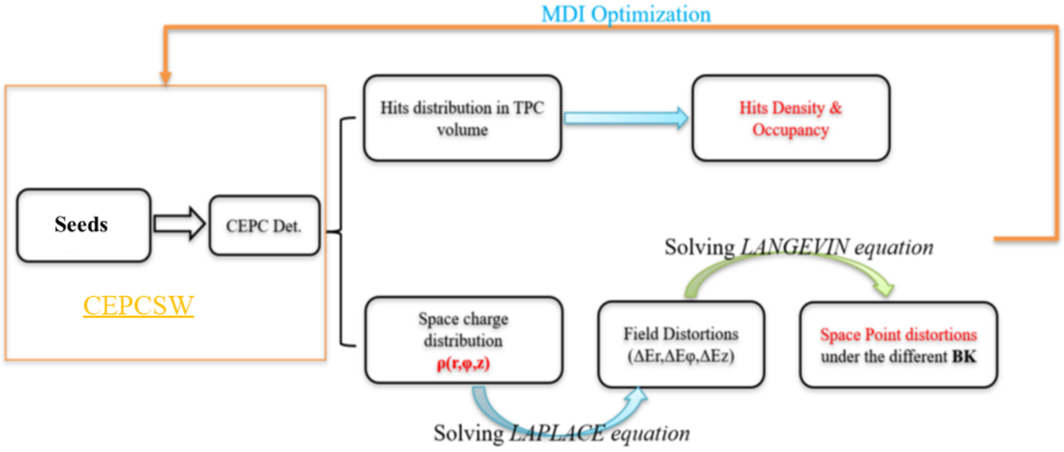
- Simulation of beam-induced background in TPC

The sources of hits/space charge in TPC

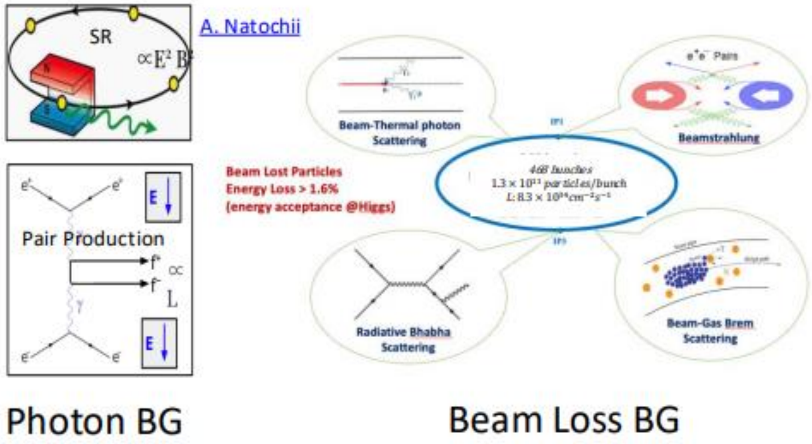
- Space charge in TPC volume：
  - Physics events: H→ss/cc/sb, Z→qq…(High P_T)
  - Beam background : (Low P_T)
    - **Beamstrahlung (**Luminosity related**)**
    - Beam-Gas, Beam Thermal Photon, SR…(Single Beam)
    - Injection background
  - IBF at the MPGDs



- Simulation flow:

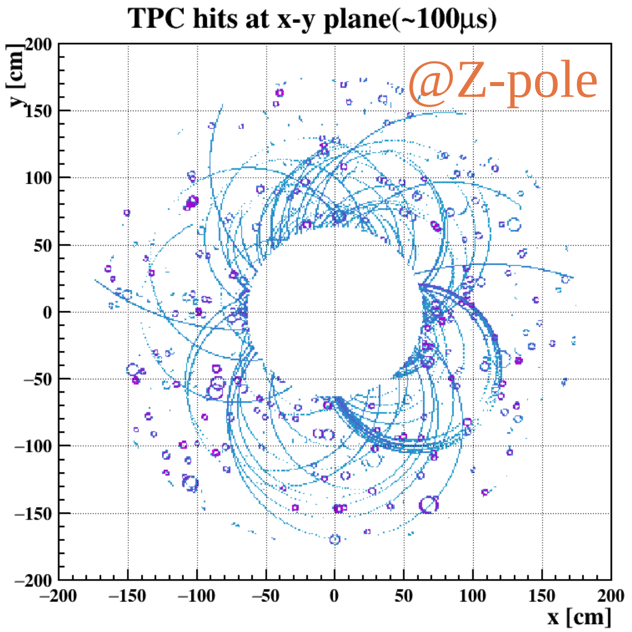


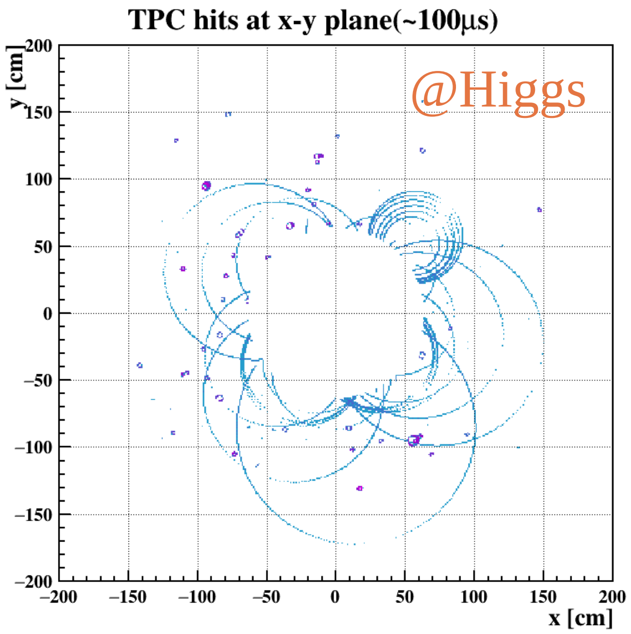
Simulation flow of CEPC Beam Backgrounds



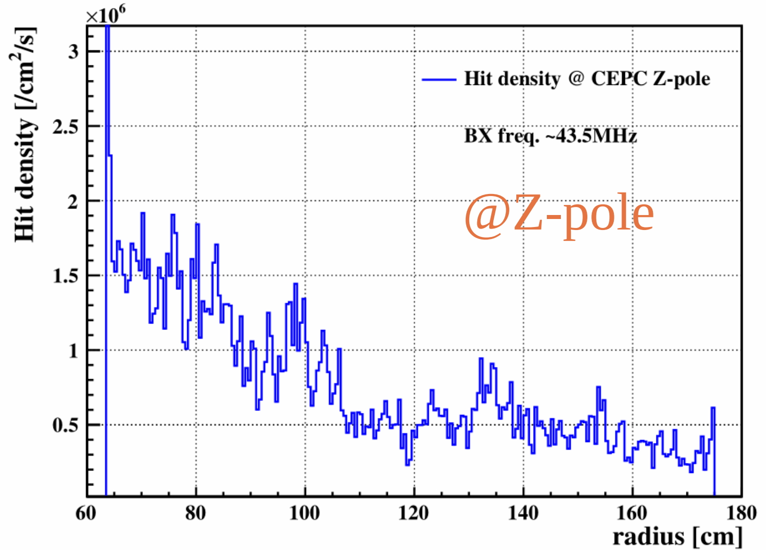
TPC hit density caused by pair-production

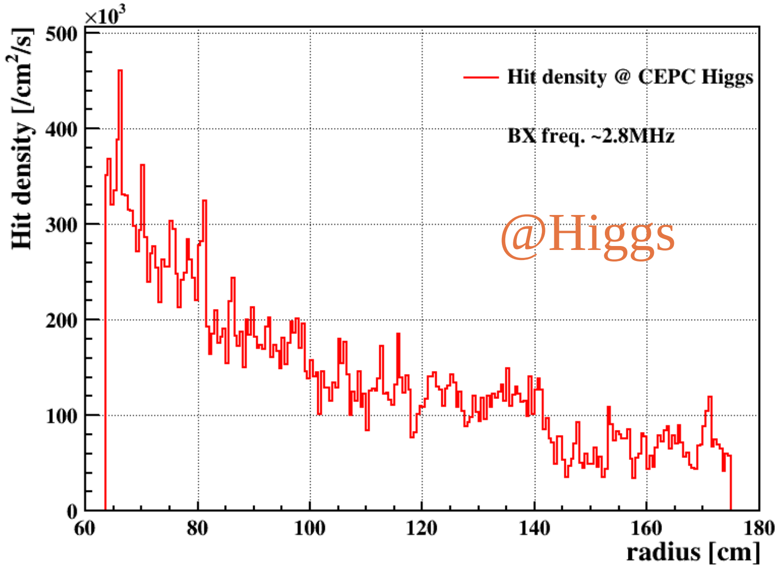
- 10000 BS file (provided by ***Haoyu Shi***) are exported to CEPCSW for full detector simulation
- All hits have been extracted to calculate the distribution of the hit density:
  - **~2 MHz /cm²/s** @Z-pole, **~0.36 MHz/cm²/s** @Higgs
  - Max. Voxel Occupancy 1.5‰ @ Z-pole, (**500um×500um** pixel, 300ns time window)
  - **Pixelated readout TPC can handle the high-count rate environment, especially for CEPC Z-pole mode**





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

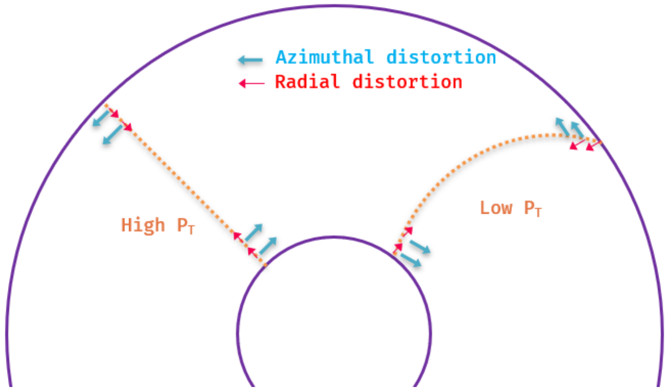




TPC hit density at a function of radius at Higgs/Z-pole mode

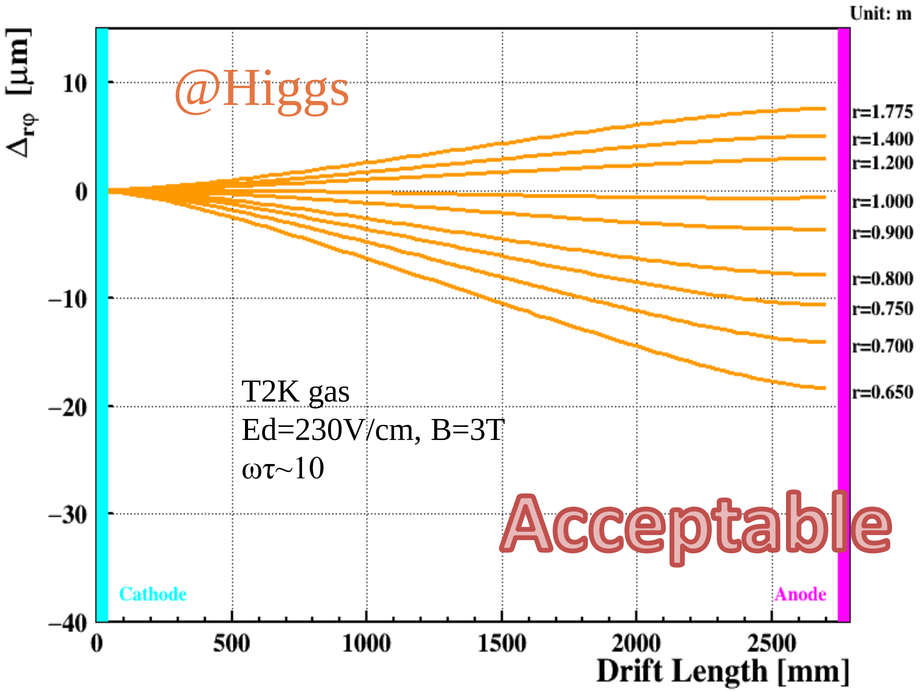
TPC distortion caused by primary ions

- Radial distortion (Δ_r) is much smaller than azimuthal distortion, almost imperceptible when along the track for most P_T track
- Azimuthal distortion ($\Delta_{r\varphi}$) has much serous impact both on high/low P_T tracks
- The maximum $\Delta_{r\varphi}$ is 20μm@Higgs (acceptable) and 150μm@Z-pole (need to optimization)

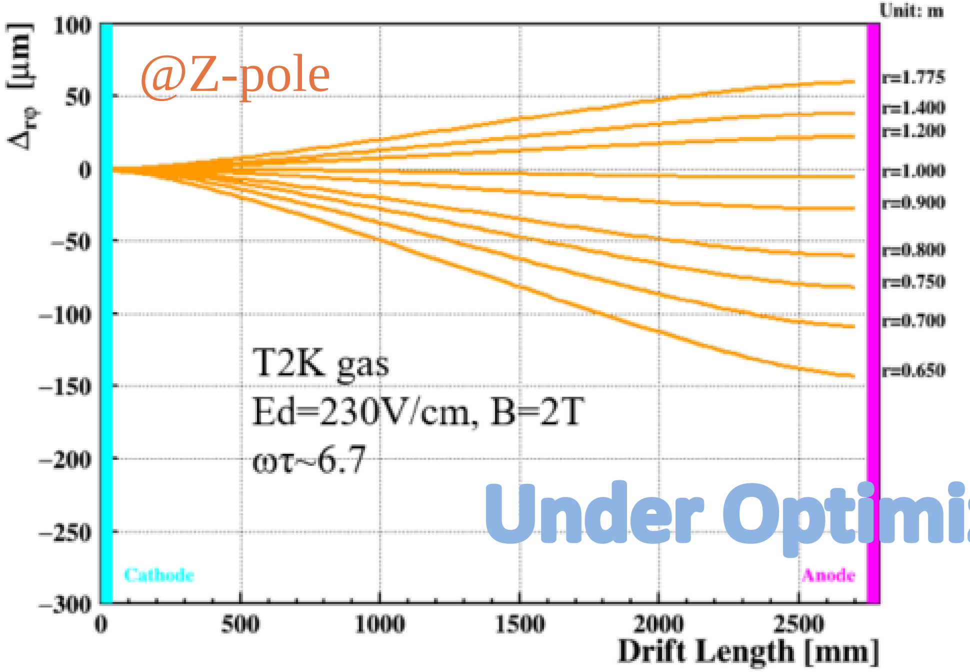


$$\Delta_{r\varphi} = \int_0^L \frac{\omega\tau}{1+\omega^2\tau^2}\times\frac{E_r}{E_z}dz$$

$$\Delta_r = \int_0^L \frac{1}{1+\omega^2\tau^2}\times\frac{E_r}{E_z}dz$$



Acceptable



Under Optimization

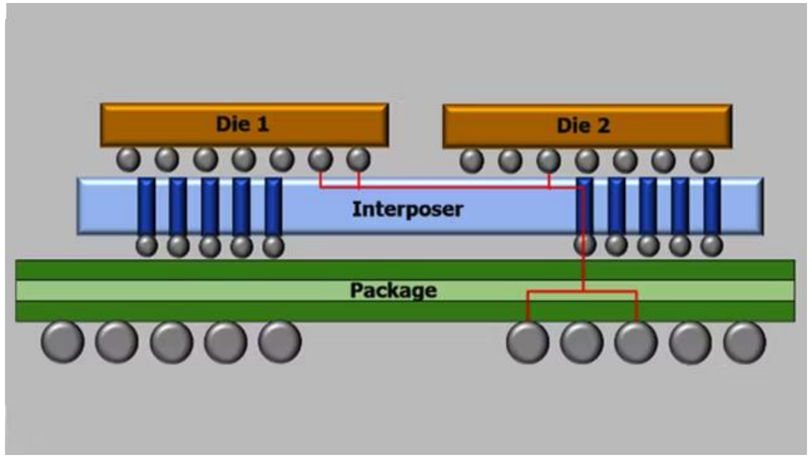
PosterID:35

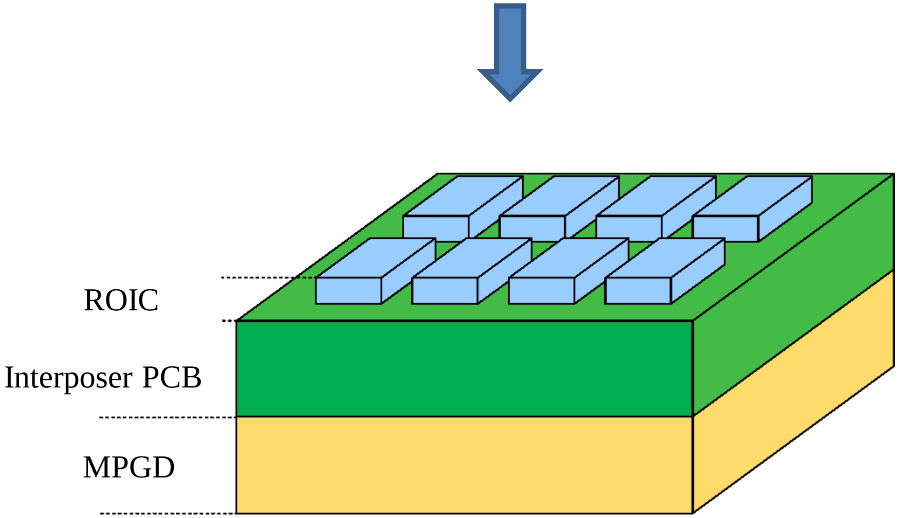
Numerical calculation results of TPC distortion based on Green's function

- Progress on Pixelated readout TPC prototype

Readout scheme for Pixelated TPC

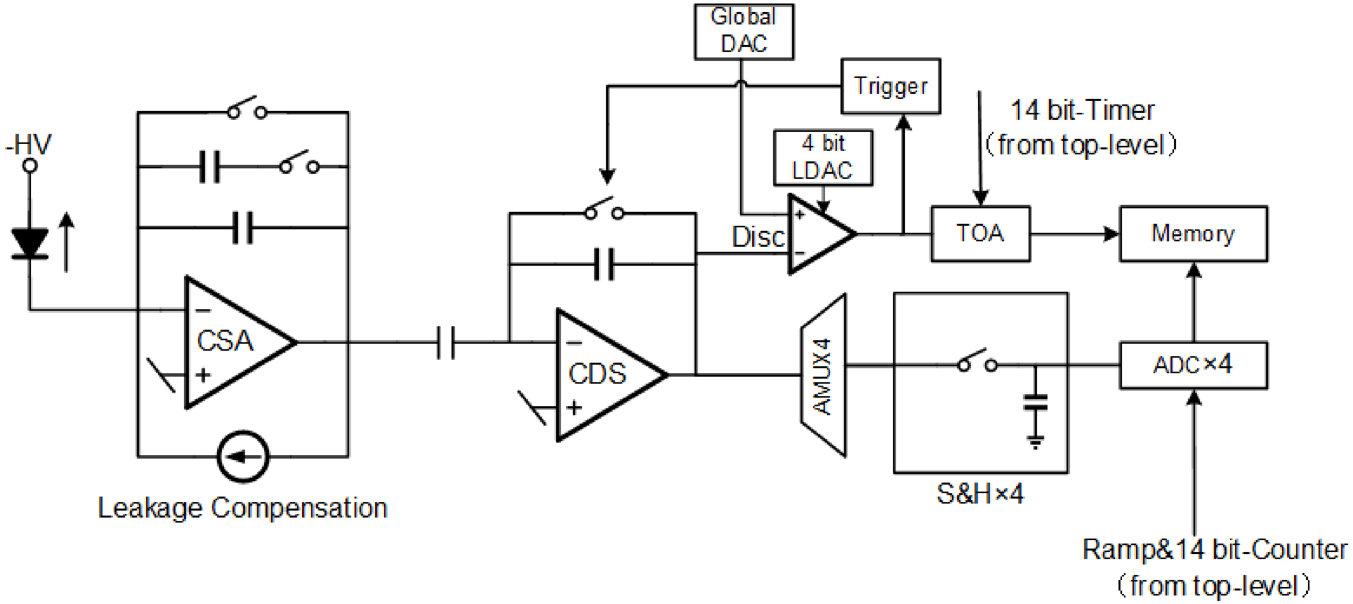
- Pixel readout electronics
  - Multi-ROIC chips + Interposer PCB as RDL
  - High metal coverage
  - Four-side buttable
- Low-power energy/time measurement ASIC： TEPIX
  - Low noise: ~100 e- noise
  - 5 ns drift time resolution
  - Low power: 100 mW/cm^2 (0.25mW/ch)

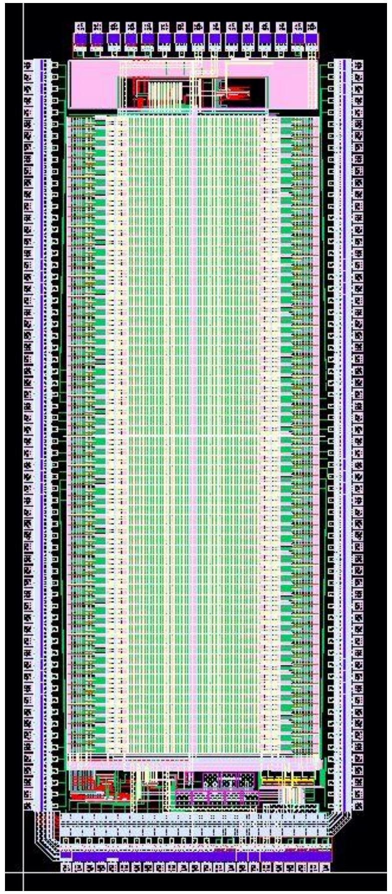




Readout ASIC for Pixelated TPC

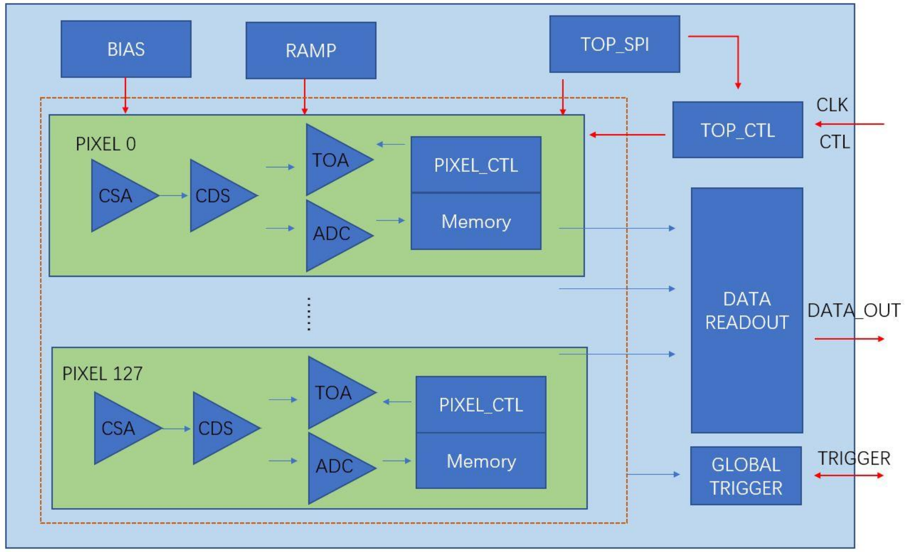
- Block diagram
  - Charge Sensitive Preamplifier(CSA)
  - CDS amplifier provides additional gain and noise shaping
  - Wilkinson type ADC each pixel
  - Timing discriminator with Time of Arrival information



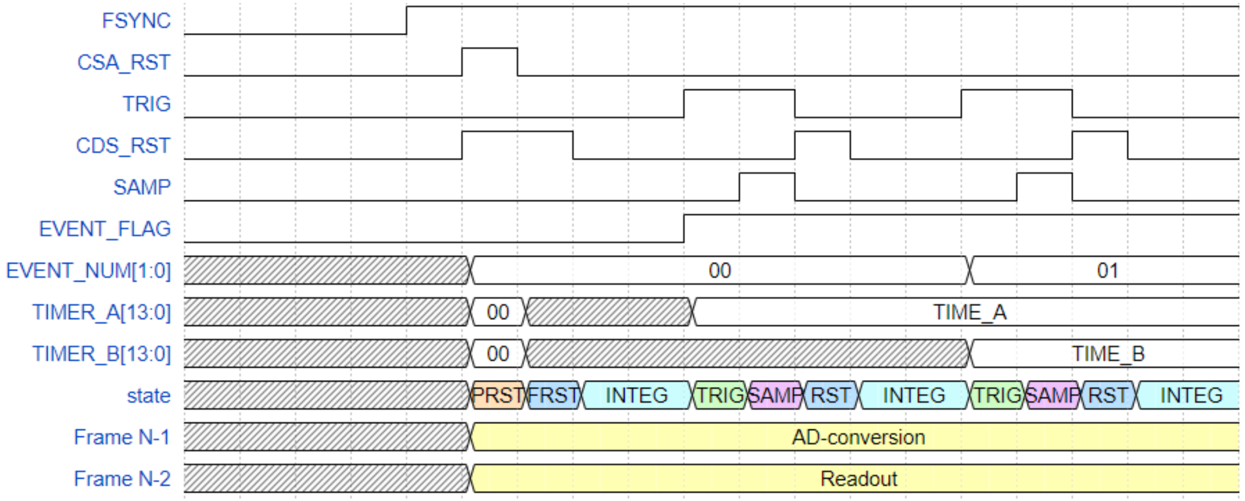


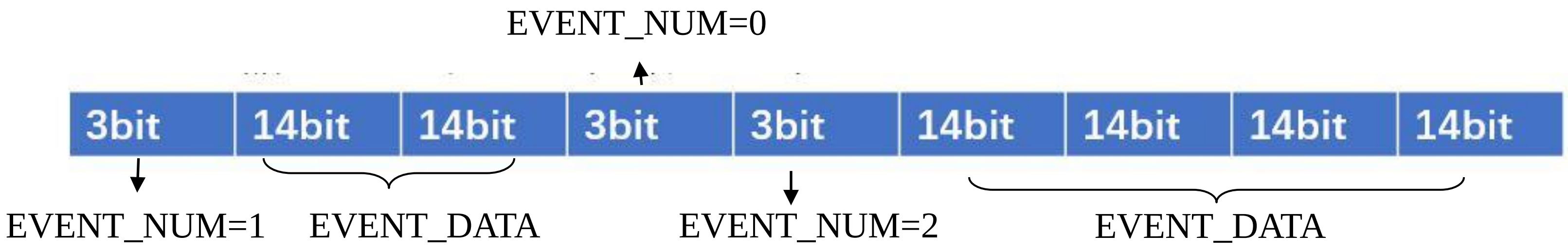
Readout ASIC for Pixelated TPC

- Top-level Design
  - On-chip data zero-compression
  - Only the fired event can be readout



Timing control part in TEPIX chips (Digital part)

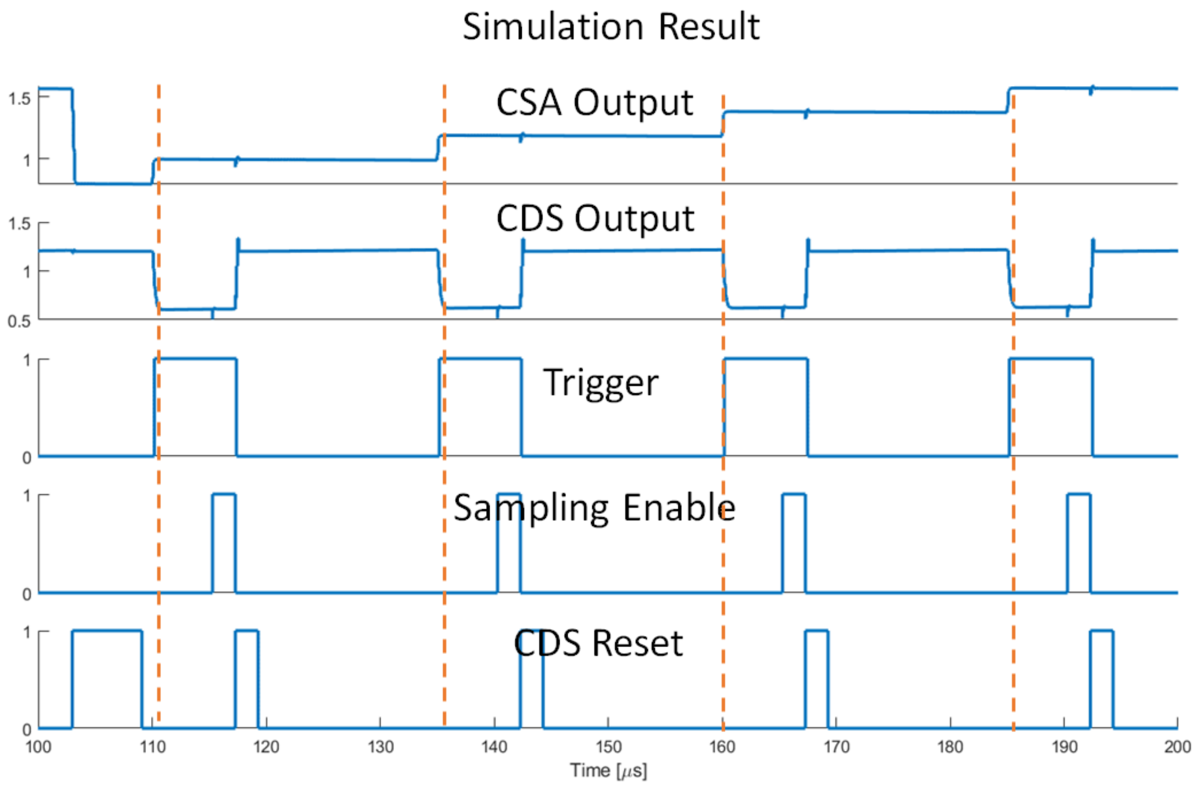




Readout ASIC for Pixelated TPC

- Waveform monitoring for outputs of CSA and CDS
- Electronic functional verification

In-pixel calibration source

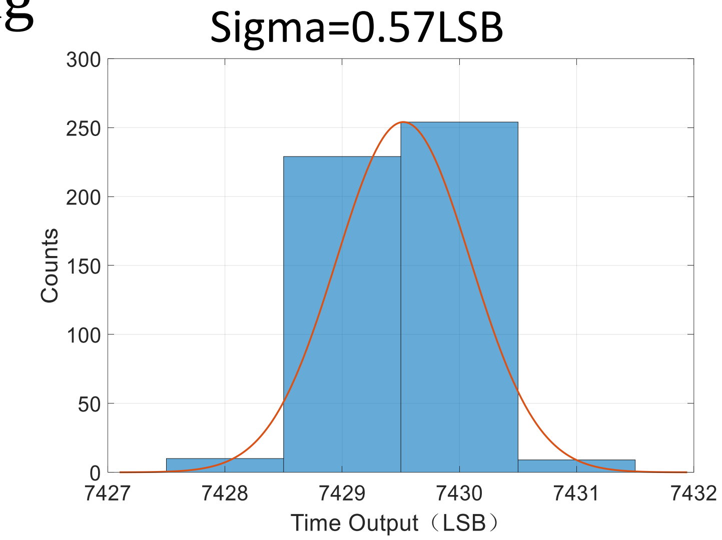


Simulation

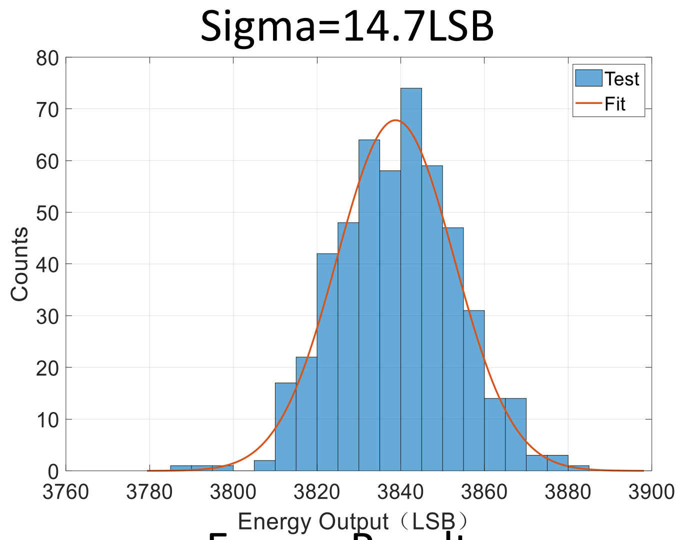
TEPIX ASIC chips test results

- TEPIX: Low power Energy/Timing measurement
  - Low power Consumption ~ 0.5mW/ch
  - Timing ~ <10 LSB(10ns)
  - Noise ~ < 300e^{-} (even high gain)

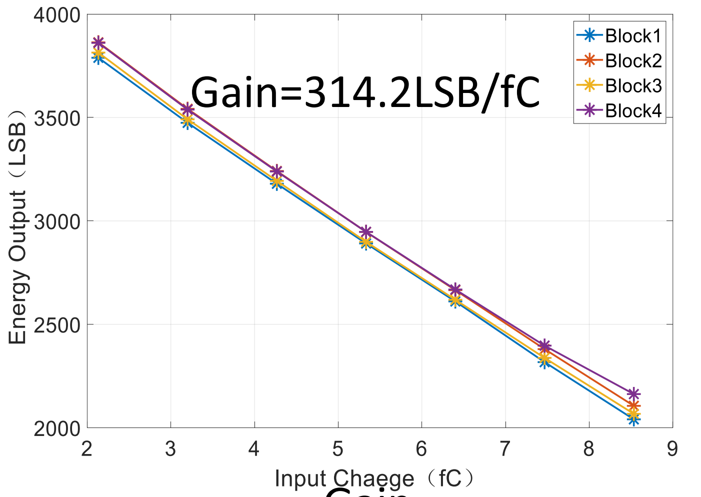
Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns



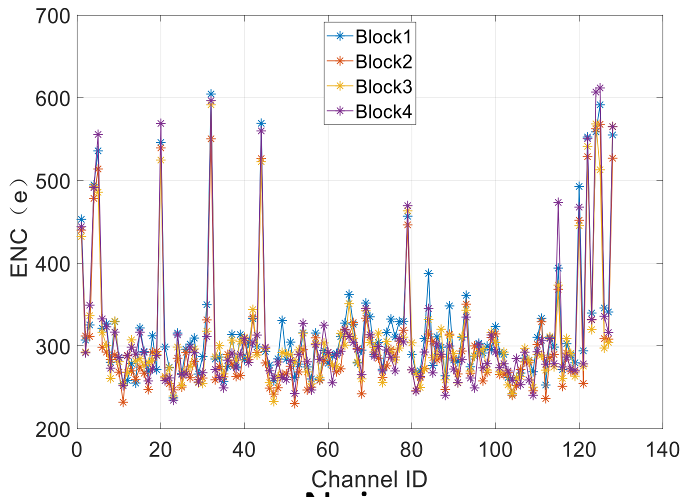
Timing Results



Energy Results



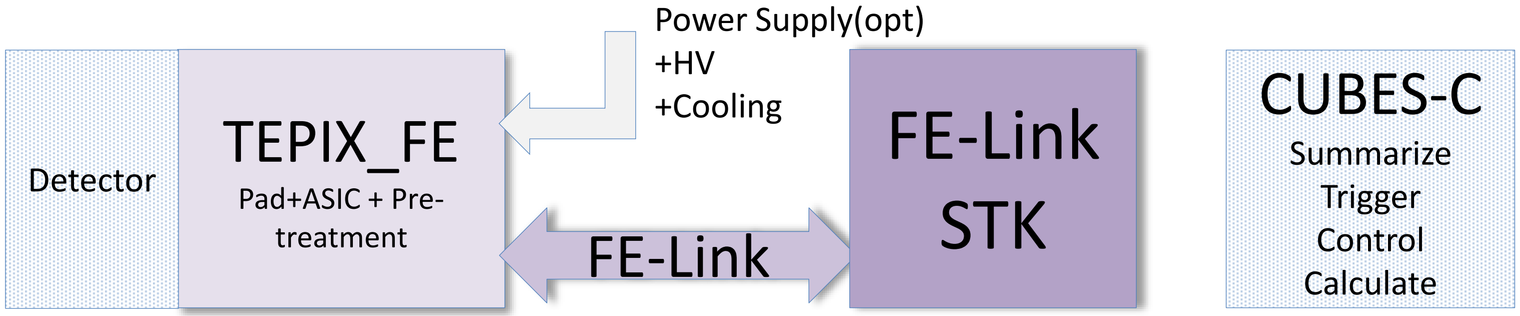
Gain

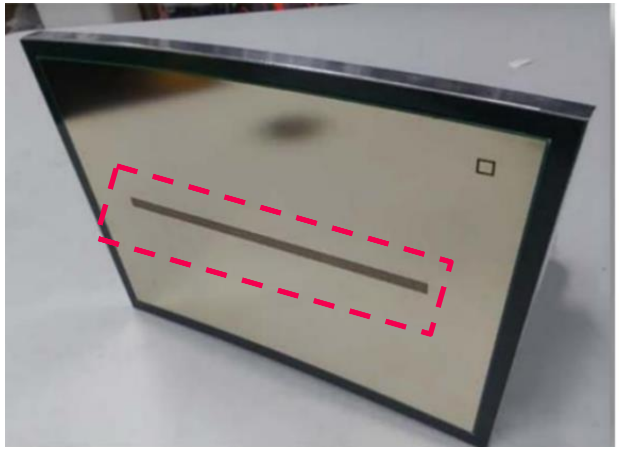


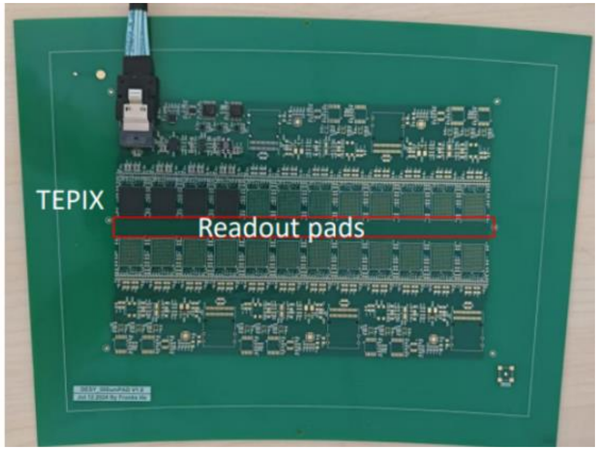
Noise

Pixelated readout TPC modules

- There are 248×2 readout modules planned for the TPC endcap in CEPC Ref-TDR
- TPC modules for Beam test:
  - Pixel size ~ 500 um×500 um
  - 10×300 readout channels
  - Can mounted in the large TPC prototype at DESY



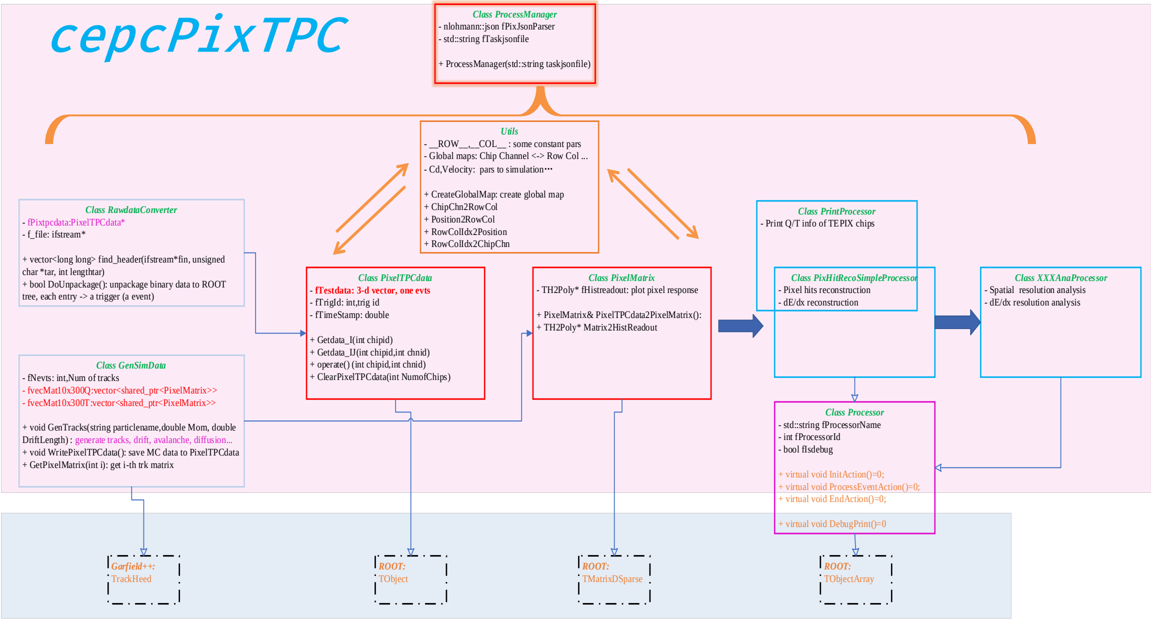


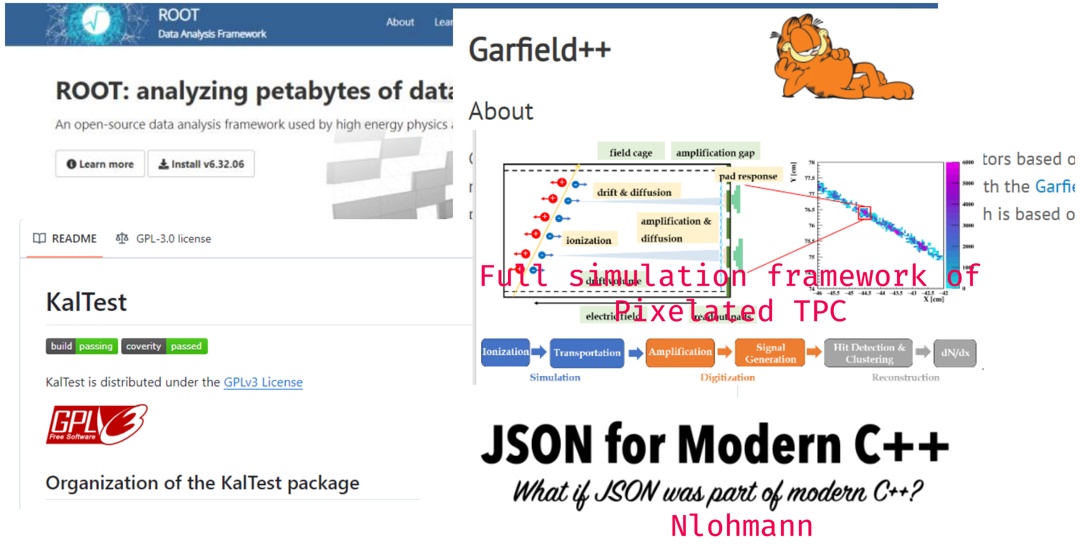


Pixelated TPC module for Beam test

Offline analysis program

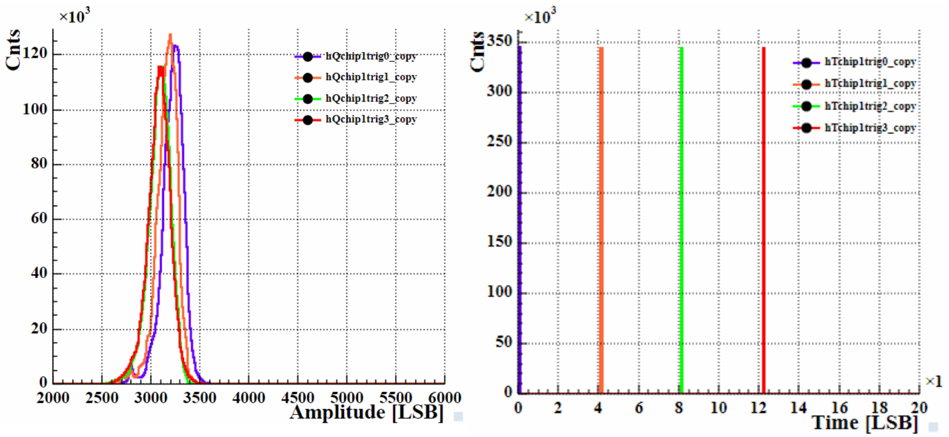
- Offline analysis program (*cepcPixTPC*) is developing
- Features：
  - Raw binary data to ROOT data
  - MC data generation
  - Chips and Channels <-> readout Pixel Mapping
  - Events reconstruction
  - …
- External libraries:
  - Full simulation framework of Pixelated TPC (Yue Chang)
  - Garfield++/ROOT, for simulation and visualization
  - KalTest, for track reconstruction and fitting
  - Nlohmann, for tasks configuration



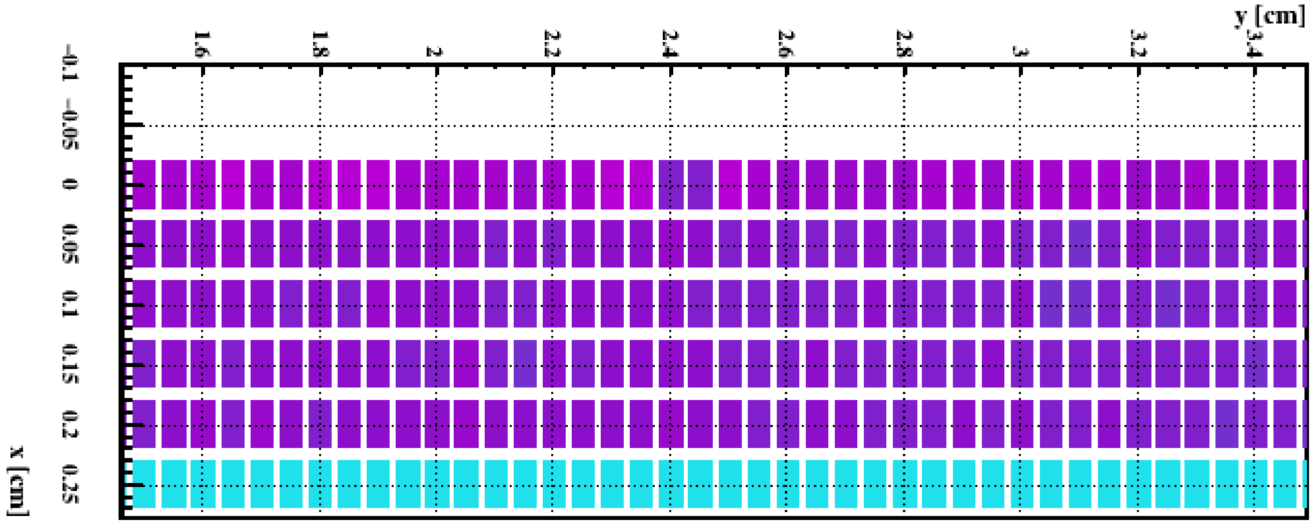


Preliminary test results with prototype

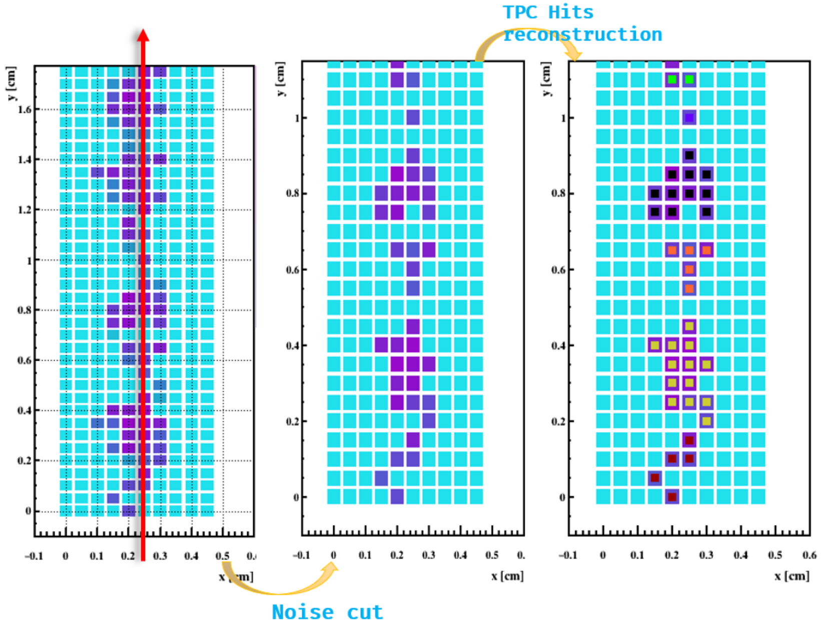
- Raw binary data from DAQ can convert to root data successfully
- Got expected energy/Trigger Time value according to the charged injected
  - Charge injected ~6fC
  - 4 Triggers, gap between each trigger 40us
- The uniformity test result : <8%
- Detailed TPC events reconstruction algorithm is under developing.



Raw data to ROOT



Readout Pixel uniformity test for 500 readout pixels



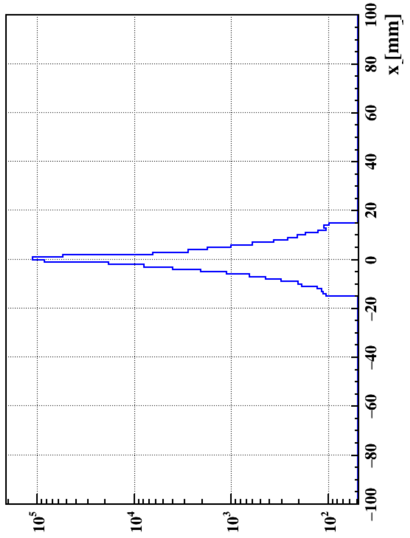
TPC hit reconstruction process

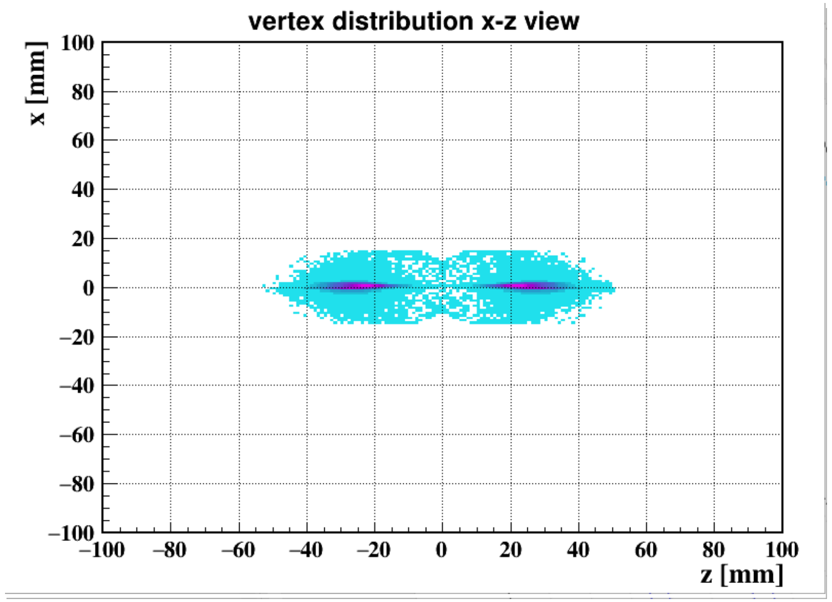
Summary

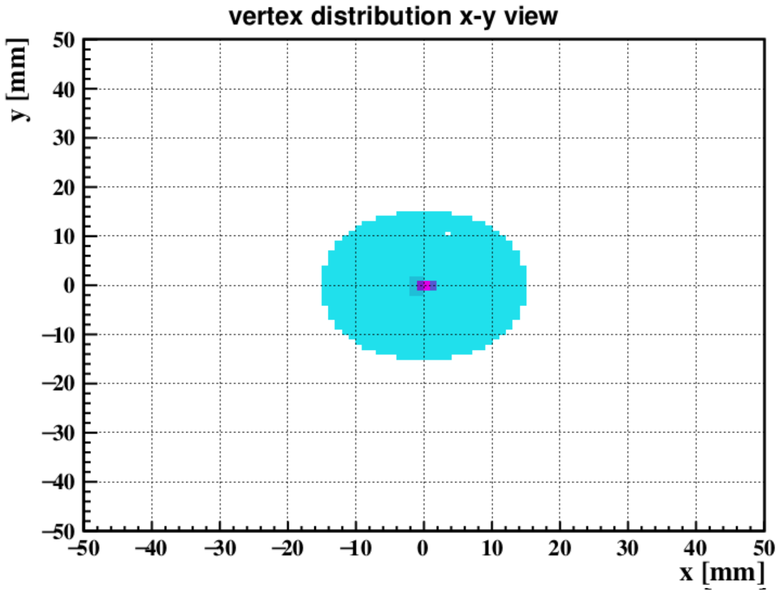
- The Pixelated TPC is the baseline main track detector and an irreplaceable tool for large 3-D track reconstruction and PID.
- Occupancy is acceptable, even for High luminosity Z-Pole
- Beam induced background has significant impact on TPC, especially at High Luminosity Z-pole conditions
- A low-power consumption pixelated readout chip TEPIX has been developed
- Validation with pixelated prototype is underway in preparation (including detector and offline program)

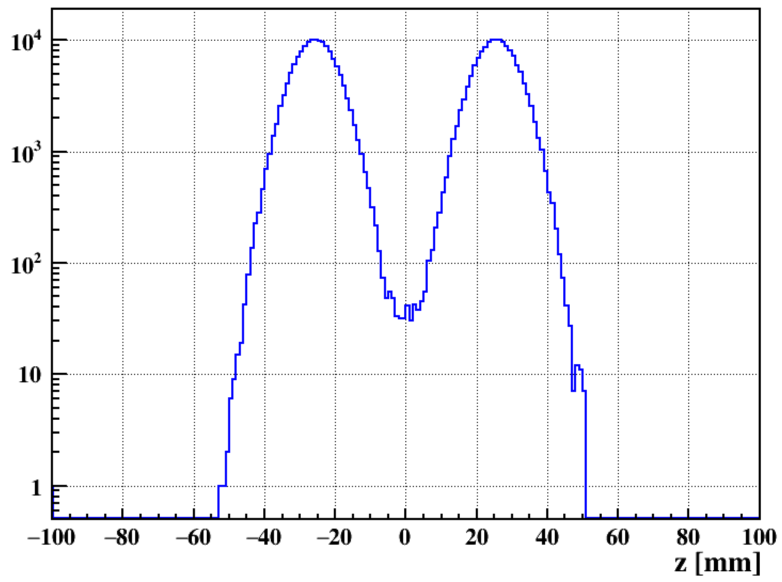
Thanks!

Back up 1: BS pairs vertex distribution

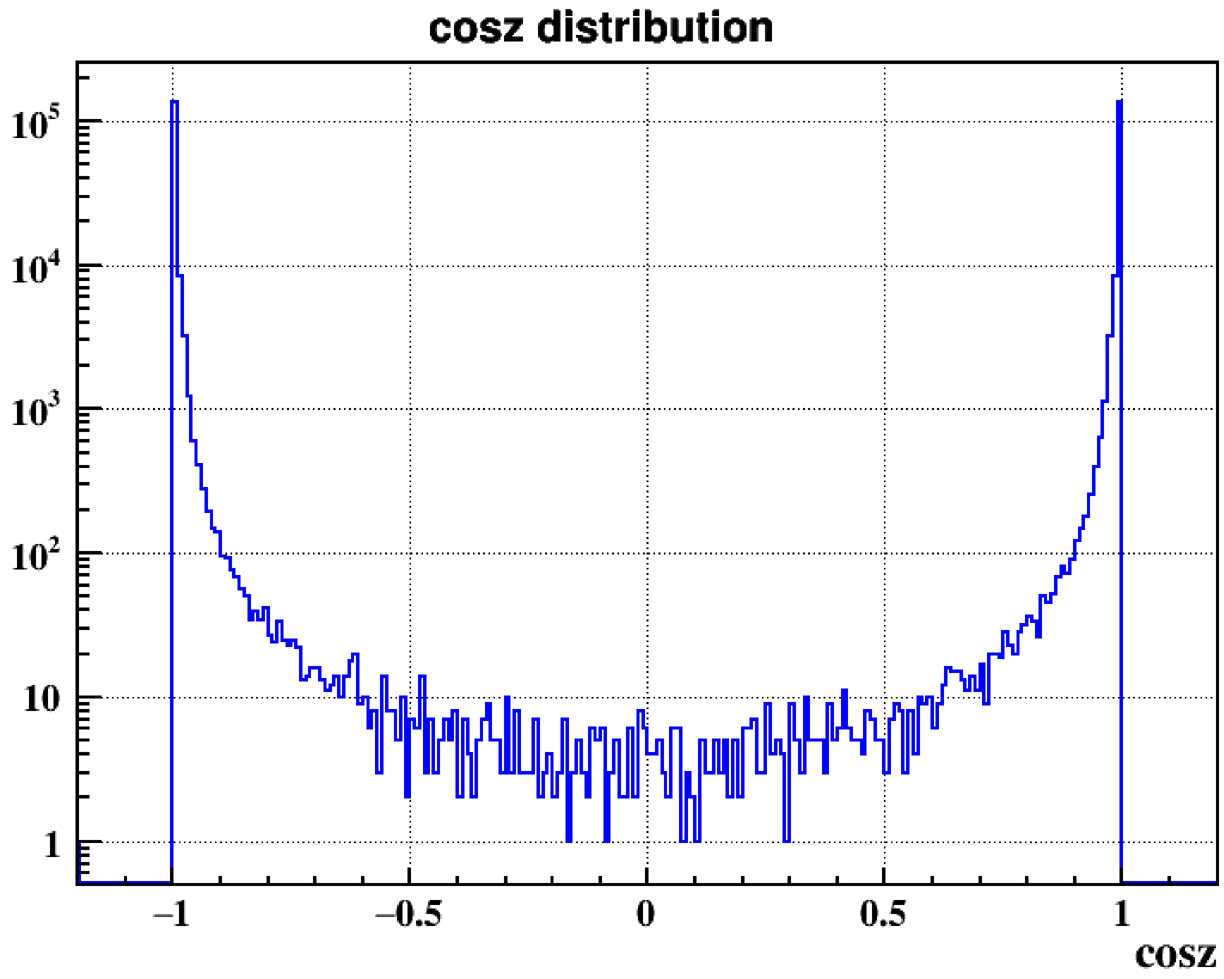




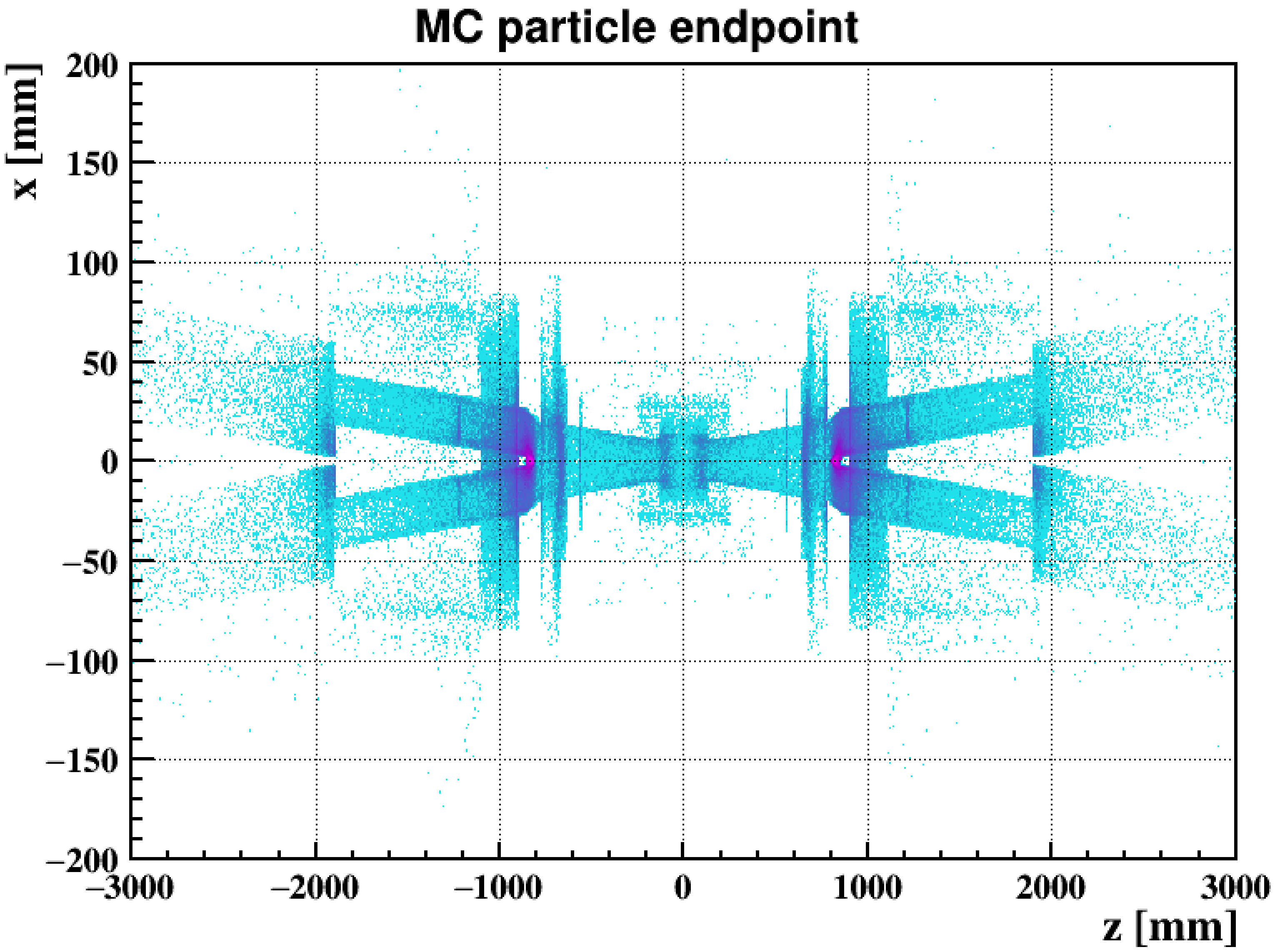




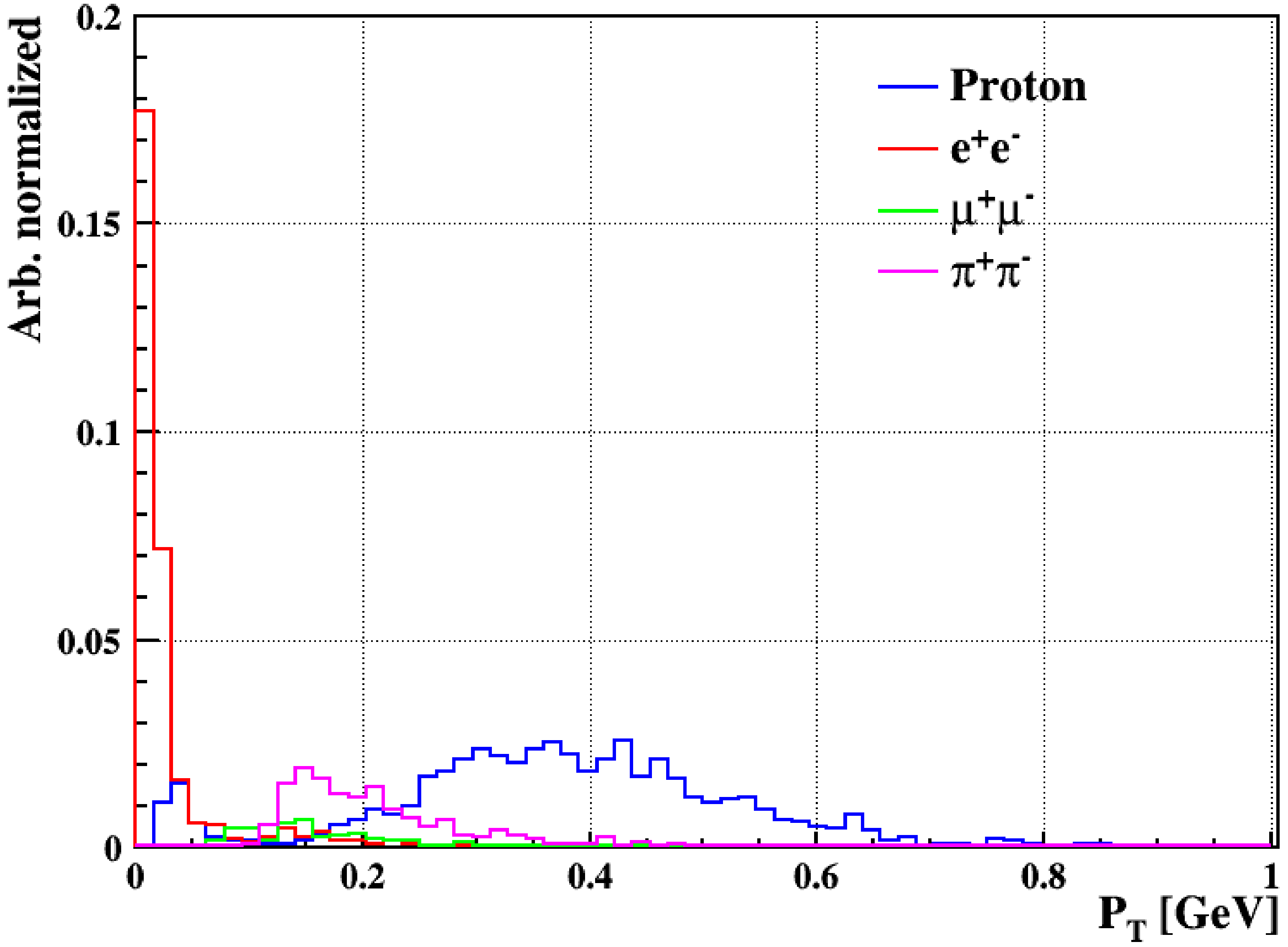
Back up 2: BS pairs cosz distribution



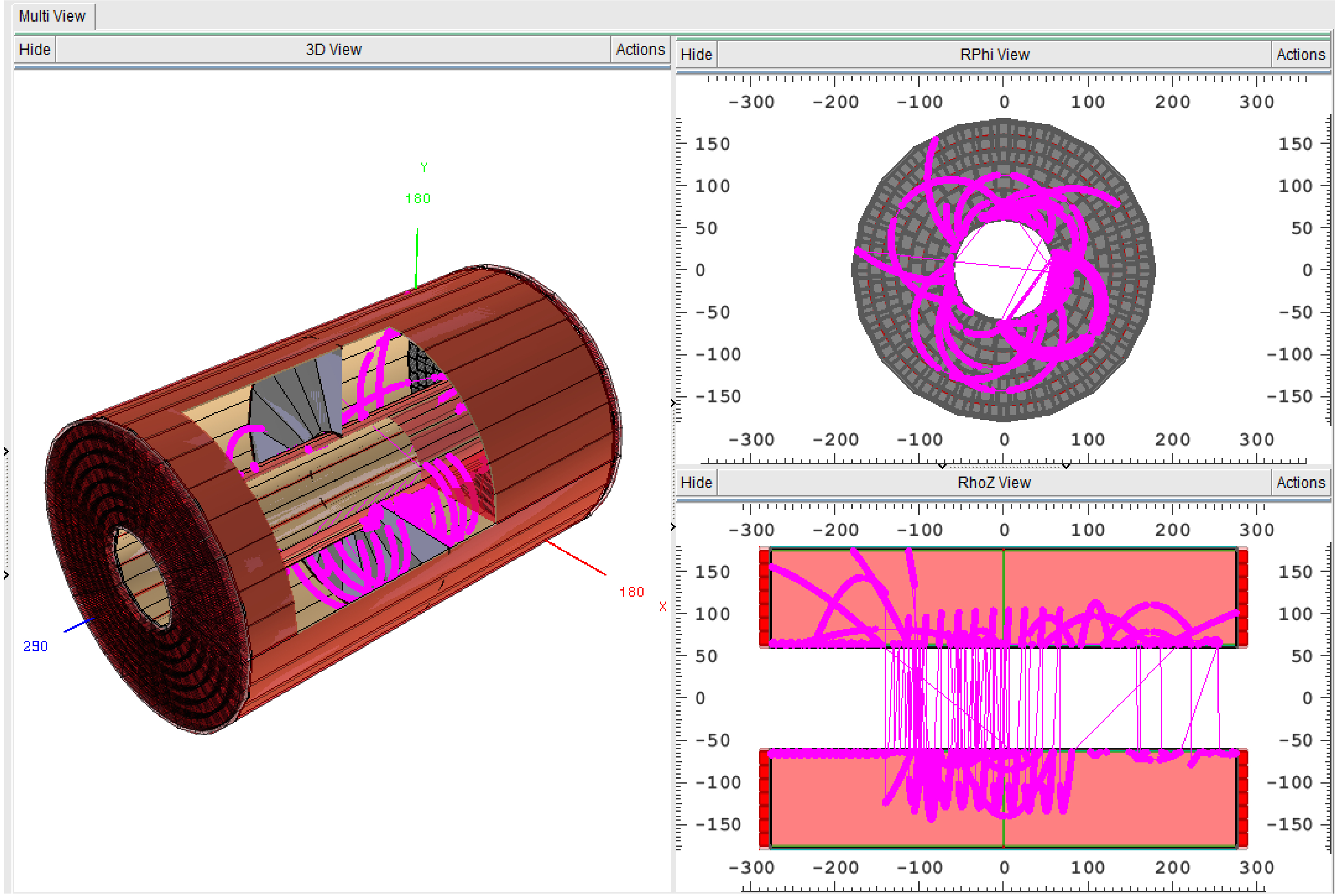
Back up 3: BS pairs endpoint



Back up 4: Pt of background particle in TPC



Back up 5: Background events display



Preliminary test result with self-calibration signal:

- Charge injected ~6fC;
- 4 triggers, gap between each trigger 40us

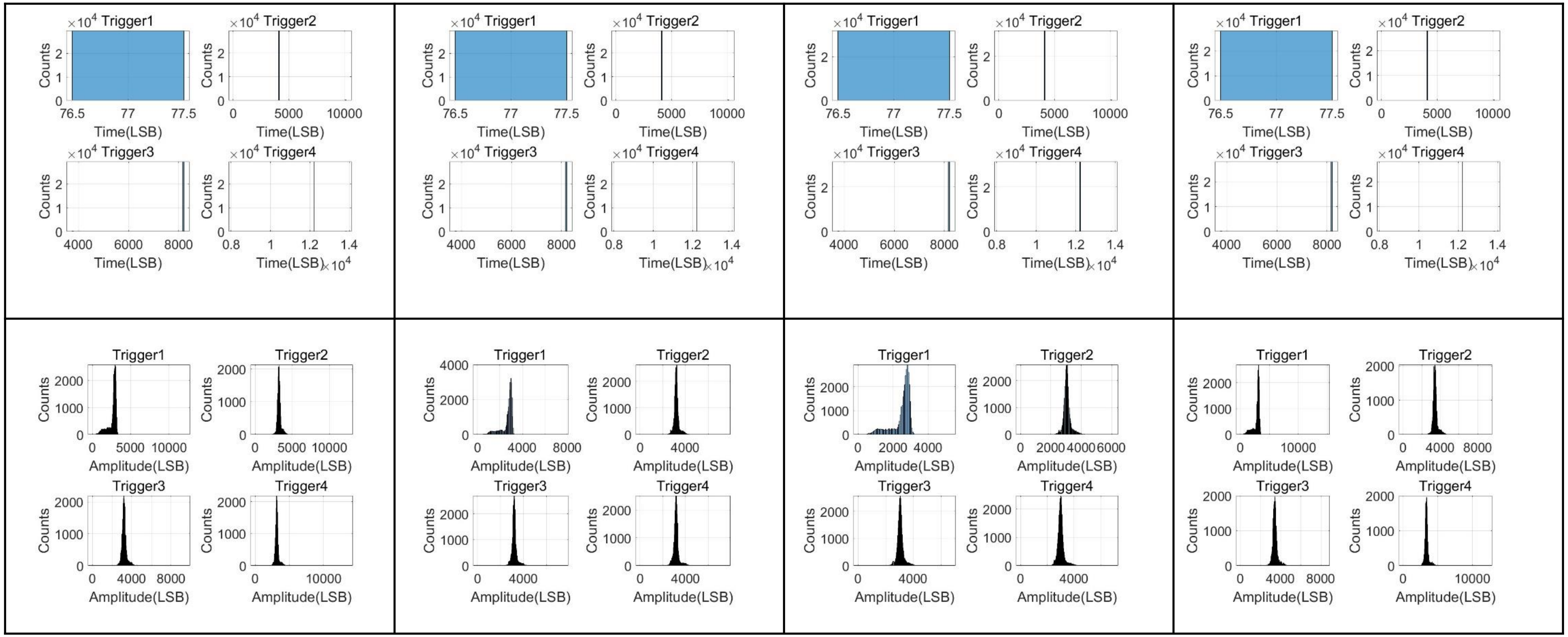
Result:

- got expected trigger time.
- got expected energy value according to the charge injected.
- some channels has lower energy of 1st trigger, need further investigation.

Trigger time and energy statistic:

Time:

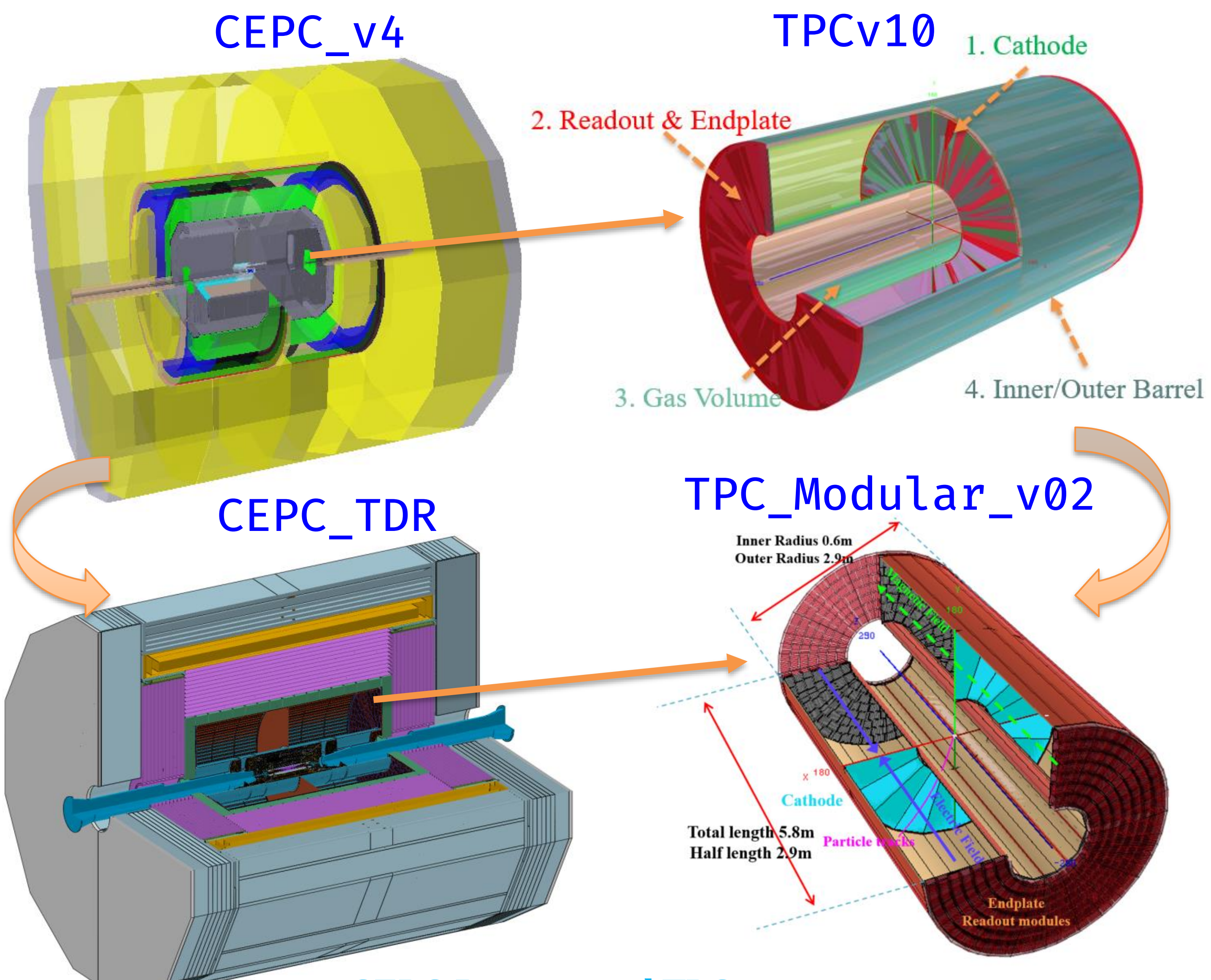
Energy:



TEPIX1 TEPIX2 TEPIX3 TEPIX4

Detector implementation in CEPC Ref-TDR

- DD4hep is adopted to provide the full detector description in CEPCSW , instead of Mokka
  - Easy to setup detectors, “Plug and Play”
- Detector models:
  - CEPC_v4: baseline detector in CDR
  - CEPC_TDR: Ref-TDR detector
- New TPC geometry has been implemented by DD4hep and exported to CEPCSW
- Verification of the new TPC geometry's material budget and hit-map has been completed
  - $0.6\%X_0$ at barrel and $\sim15\%X_0$ at Endplate



CEPC Detector and TPC geometry

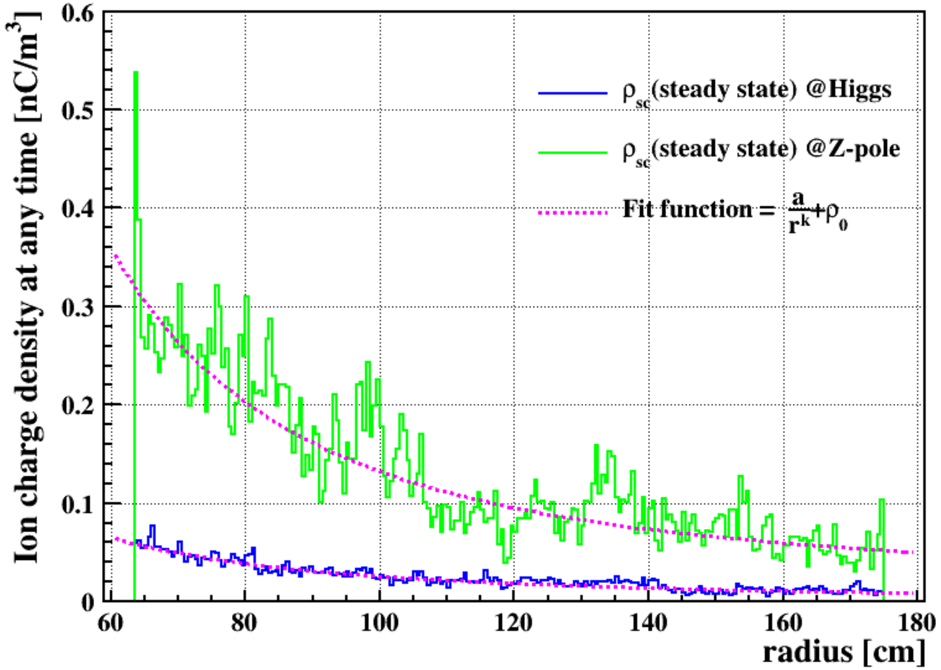
Space charge density in TPC

- Number of primary ions can be calculated by Edep/effective ionization potential of Ar [26 eV]
- The ion charge density at any time is given by:

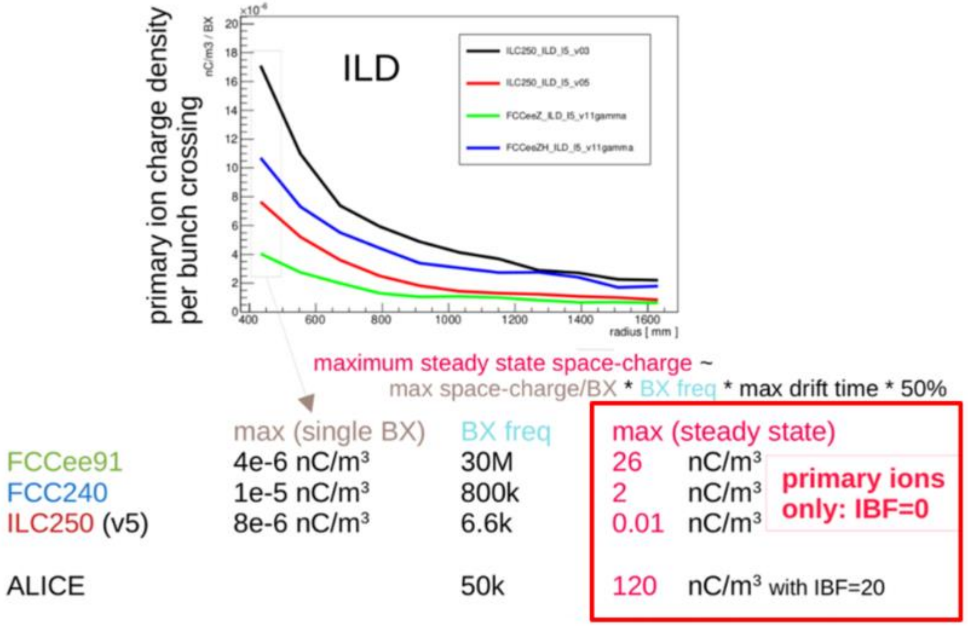
~0.55s assuming 5m/s ion drift velocity

Ref Daniel Jeans' slides

  - ρ_{sc} ~ primary ions/BX × BX frequency × max drift time of ion × 50% [ion already reached cathode]
  - BX frequency: 1/23ns @Z-pole, 1/355ns @Higgs
- The space charge in CEPC TPC is ~50× smaller than FCCee, ref KEK ***Daniel Jeans*** simulation results



Space charge density at Higgs/Z-pole mode



Beam background in a TPC at a circular collider

Calculation method of the distortion

- Distorted electrical field can be solved analytically based on Green's function:

➤ The potential due to a arbitrary space charge density can be evaluated via:

$$\Phi(r,\varphi,z)=\frac{1}{\epsilon_0}\int r'dr'\int d\varphi'\int dz'\rho_{sc}(r',\varphi',z')\cdot G(r,\varphi,z;r',\varphi',z')$$

➤ For distorted transverse electrical filed (average over φ) :

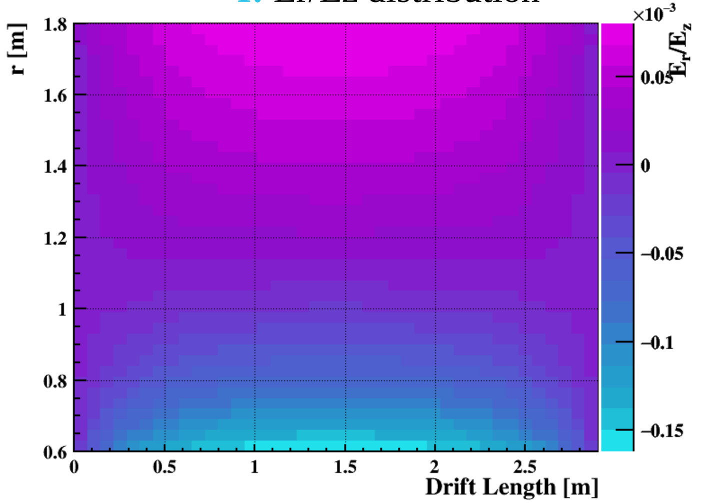
$$E_r(r,z)=\frac{2}{\epsilon_0 L}\sum_{n=1}^{\infty}\frac{\sin\beta_n z}{R_0^0(\beta_n,a,b)}\int_0^L \sin(\beta_n z')dz'[$$

$$(K_0(\beta_n a)I_1(\beta_n r)+I_0(\beta_n a)K_1(\beta_n r))\int_r^b r'R_0^0(\beta_n,b,r')\rho_{sc}(r')dr'+$$

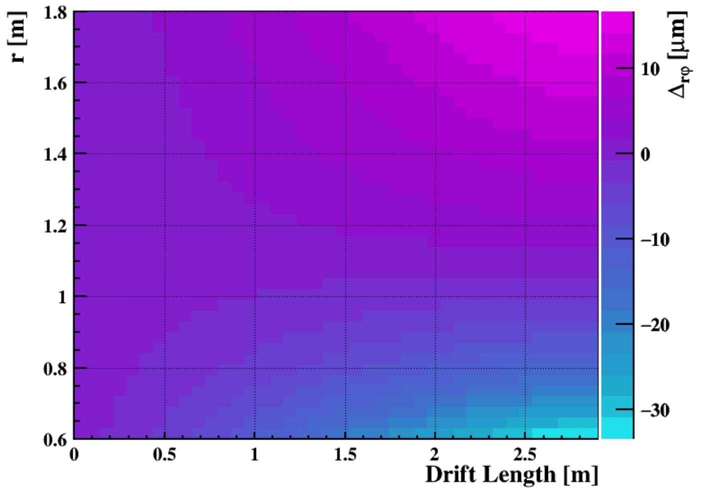
$$(K_0(\beta_n b)I_1(\beta_n r)+I_0(\beta_n b)K_1(\beta_n r))\int_a^r r'R_0^0(\beta_n,a,r')\rho_{sc}(r')dr']$$

In practice, n>200, $\beta_n > n\pi/L$

I: Er/Ez distribution



II: Distortion distribution



➤ TPC distortions under different drift length:

LANGEVIN equation: $m_e\frac{d\vec{v}}{dt}=e\cdot\vec{E}+e\cdot(\vec{v}\times\vec{B}-k\cdot\vec{v})$

Ref K. Fujii and ALICE slides

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

$$\omega\tau = BField[kGauss]*\frac{-10.\ *\ |Drift\,Velocity[cm/\mu sec]|}{|Electric\ Drift\ Field\ Strength\ [V/cm]|}$$