



Status of the high granularity readout TPC technology in CEPC Phy.&Det. TDR

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On behalf of the CEPC gaseous tracker R&D group & LCTPC Collaboration

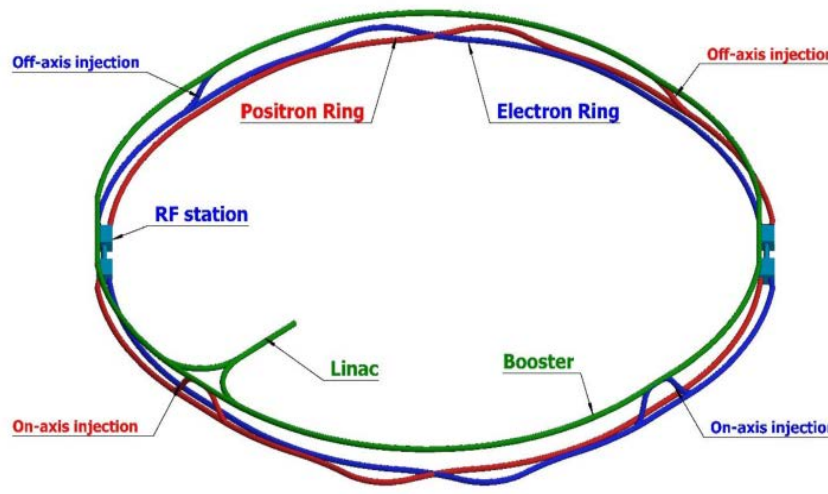
DRD1 Collaboration Meeting, 07 October 2025, Warsaw, Poland

- **Motivation**
- **Status of TPC in CEPC TDR**
- **Simulation and Prototype**
- **Work plan and summary**

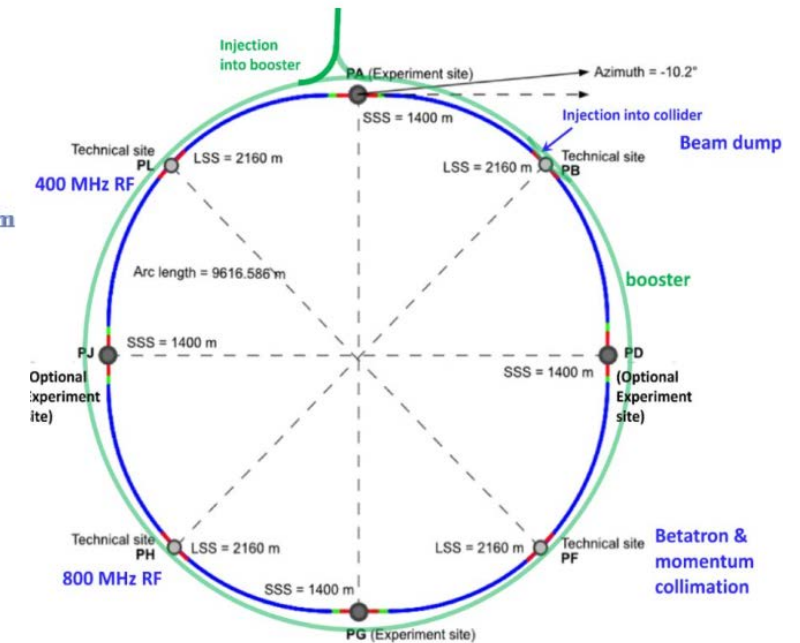
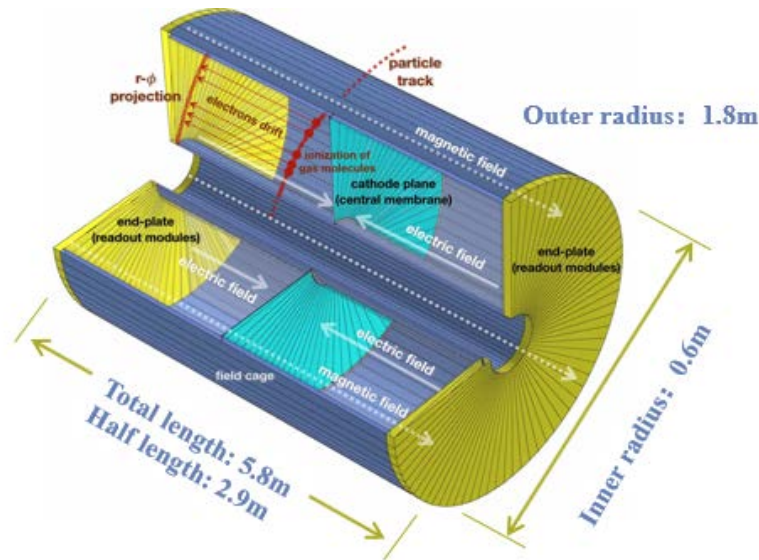
- **Motivation**

Motivation

- A TPC is the main track detector for some candidate experiments at future e^+e^- colliders.
 - **Baseline detector concept** of ILD at ILC and CEPC
- TPC technology can be of interest for other future colliders (EIC, FCC-ee).
- High granularity readout readout TPC can improve **PID requirements of Flavor Physics at e^+e^- collider**.



Circular Electron Positron Collider (CEPC)

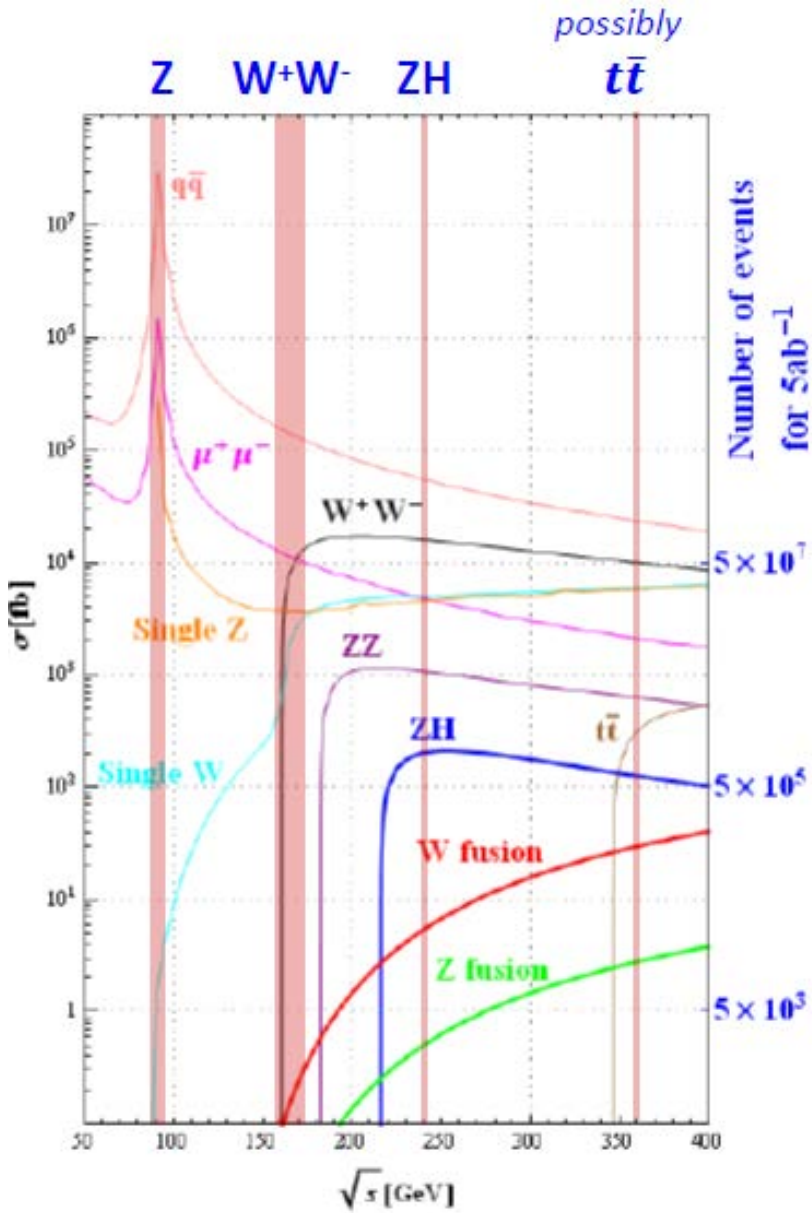


Future Circular Collider (FCCee)

Operation plan in CEPC

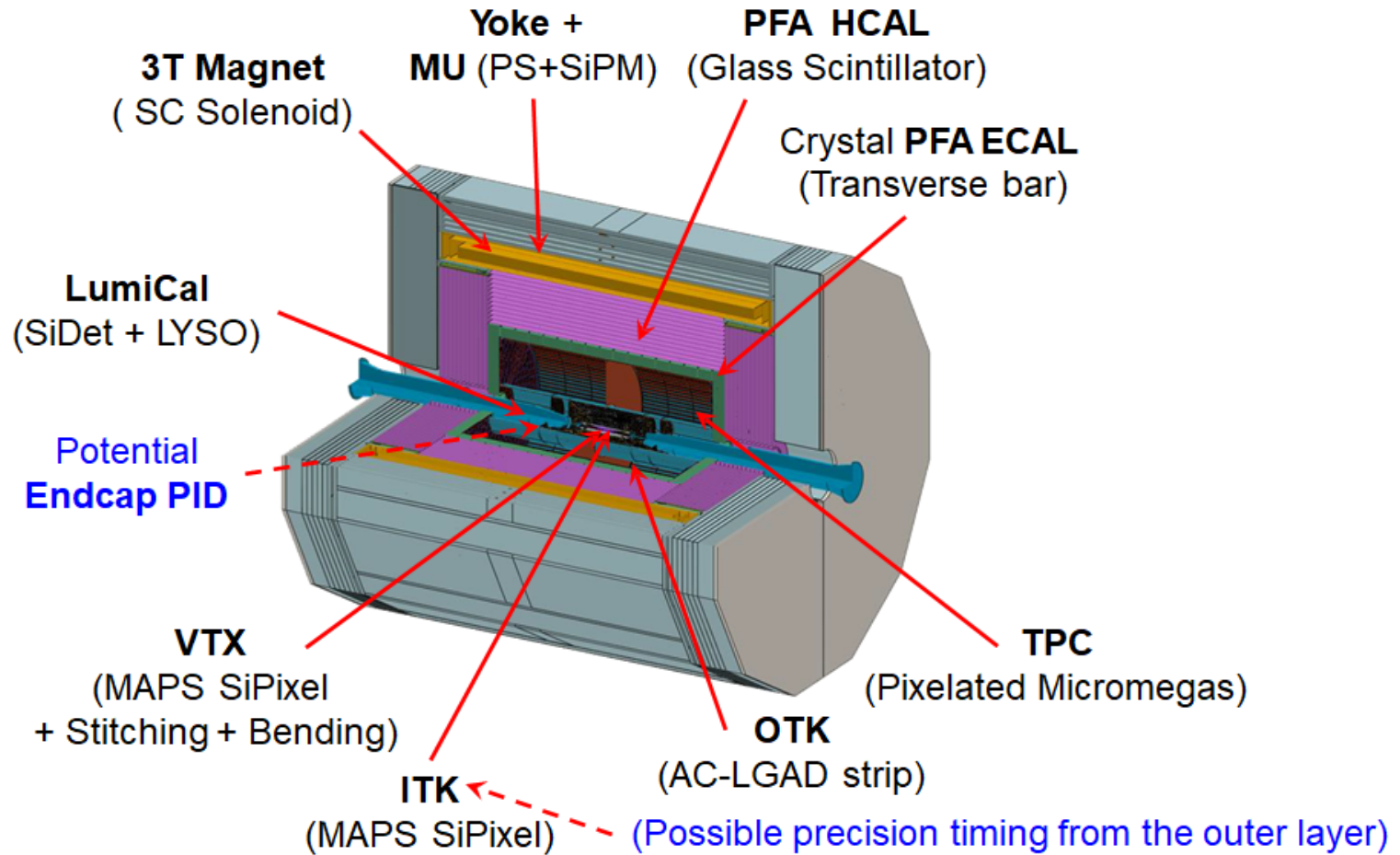
- The CEPC Accelerator TDR document was released at the end of 2023.
- In the operation plan, the **first 10-year** operation includes: the Higgs mode, Low-Lumi Z mode, and WW mode (B = 3.0T).
- The accelerator may be upgraded for High-Lumi Z mode and/or tt mode after 10 years operation, subject to physics needs.

SR Power Per Beam	Luminosity/IP [$\times 10^{34}\text{cm}^{-2}\text{s}^{-1}$]		
	H	Z	W+W-
12.1 MW	-	26	-
30 MW	5.0	-	16
50 MW	8.3	-	26.7



Baseline Detector Design in TDR

- Will explore the possibilities of
 - A forward PID detector inside TPC
 - The outer layer ITK also provides precision timing
- After 10-year operation, the majority will remain, a few may be upgraded, including
 - VTX: for a better performance and radiation tolerance
 - TPC: to deal with higher luminosity

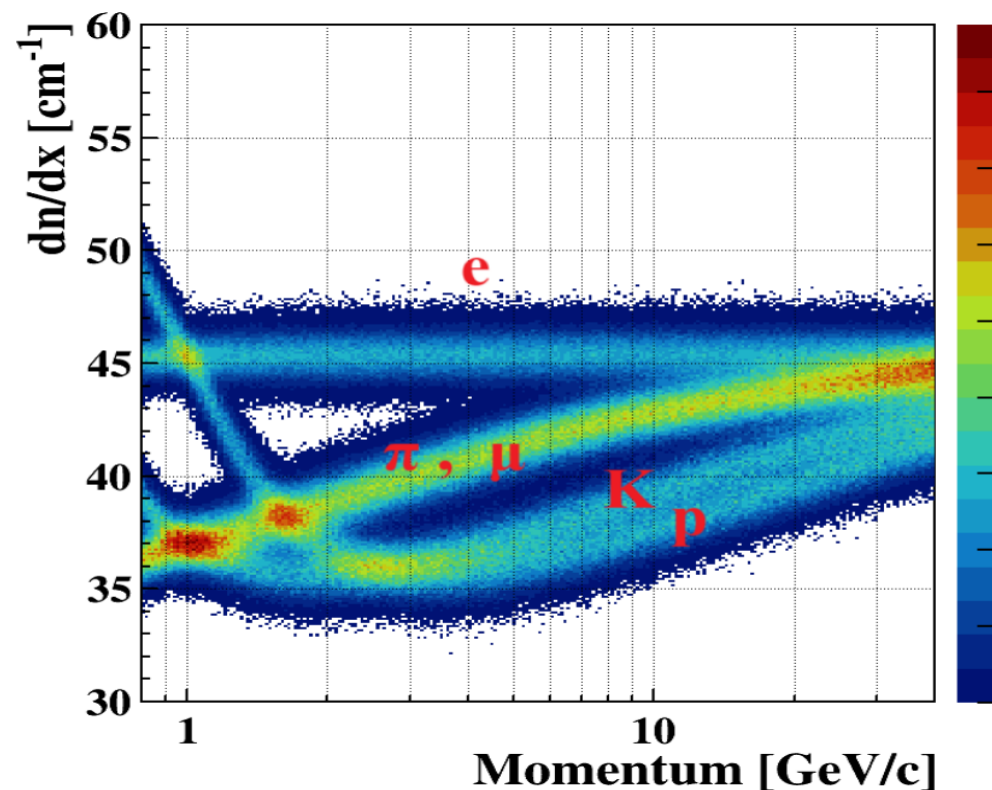
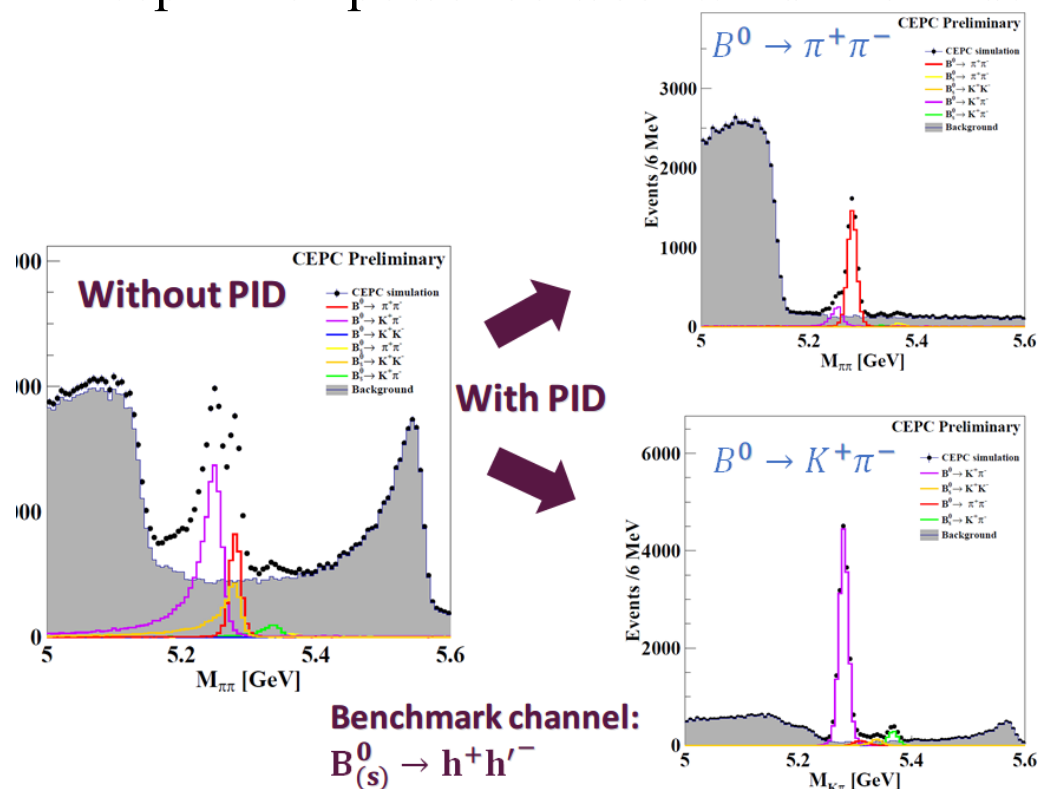


- **Status of TPC in CEPC TDR**

Physics requirements in CEPC

- Circular e⁺e⁻ collider operation stages in TDR: **10-years Higgs @3T → 2-years Z pole → 1-year W**
- Gaseous tracker leading contribution to PID and the high resolution: jet & differential
 - High granularity readout readout and better than 2σ separation power between π and k for P using dn/dx

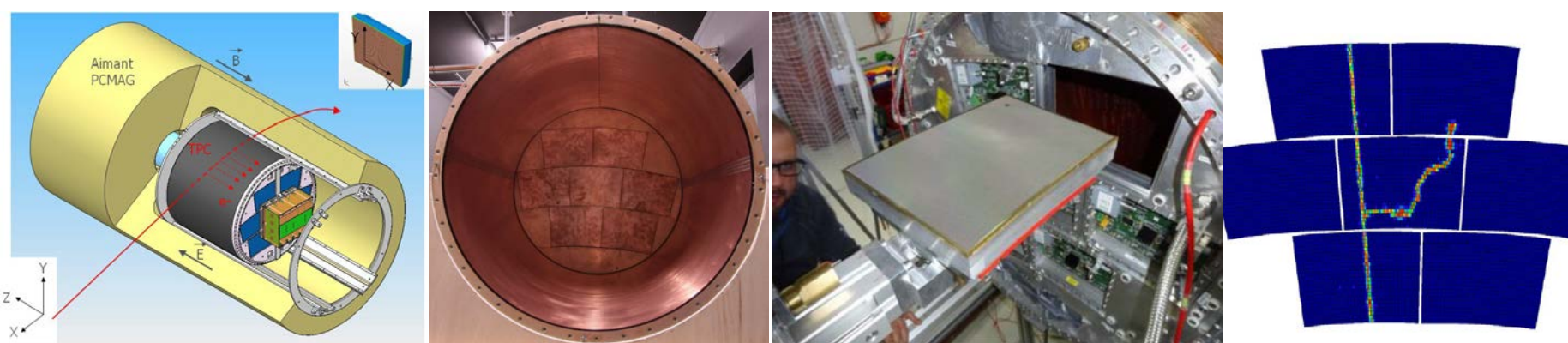
Calibration: Low luminosity Z at 3T
 Approximately $10^{35} \text{cm}^{-2} \text{s}^{-1}$
 20% of high luminosity Z



Status of Pad readout TPC in LCTPC

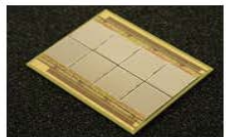
- **Large Pad readout Prototype** setup has been built to compare different detector readouts under identical conditions and to address integration issues.
 - PCMAG: $B < 1.2\text{T}$, bore $\varnothing$: 85cm
 - Two end plates for the LP made from Al with 7 module window
- **LP Field Cage Parameter**
 - Length = 61cm, inner $\varnothing$ = 72cm drift field up to $E \approx 350\text{V/cm}$
 - Made of composite materials: 1.24 % X_0

JINST 5: P10011, 2010
JINST 16: P10023, 2021



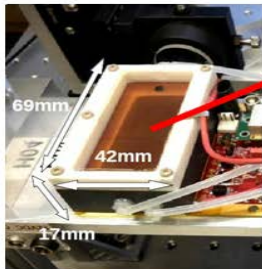
Status of Pixelated readout TPC in LCTPC

- GridPix detector have moved from Timepix to Timepix3 ASICs. Tests with quad devices have been successfully done under $B=1.0T$ at DESY in 2021 and 2022.
- Very high detection efficiency results in **excellent tracking and dE/dx performance**. Timepix4 development is ongoing.
 - All results showed that **a pixel TPC is realistic.**($\sim 10^6$ events)

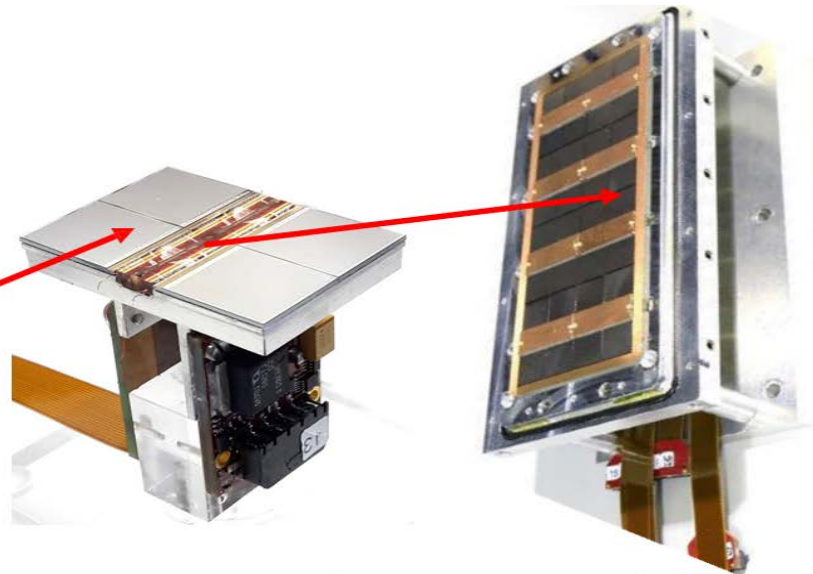


(Octopuce)

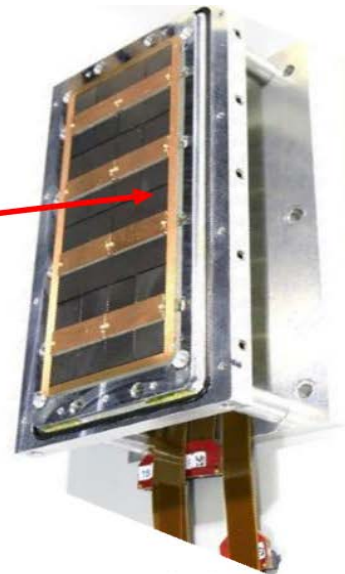
TimePix1
2007



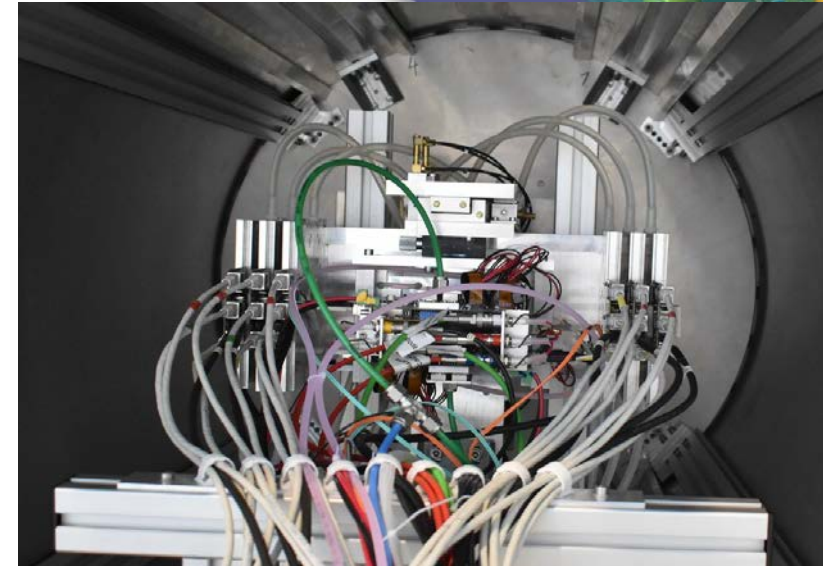
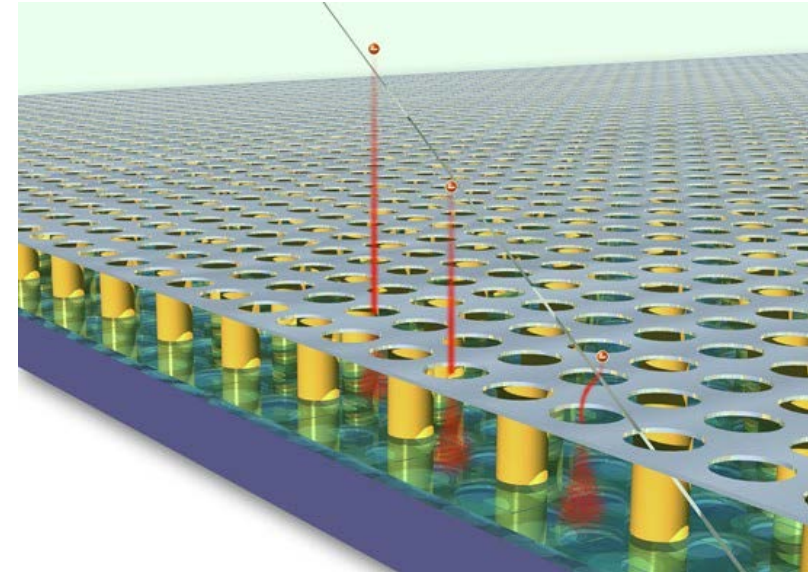
TPX3 chip
2017



Quad
2018



Module
2019



NIM A535 (2004) 506-510
NIM A845 (2017) 233-235

High granularity readout TPC technology in CEPC TDR

TPC technology detector for e^+e^- collider

Pad readout TPC

- To meet Higgs physics
- $1\text{mm} \times 6\text{mm}$ of Pad
- $< 100\text{mW}/\text{cm}^2$
- dE/dx



Pixelated readout TPC

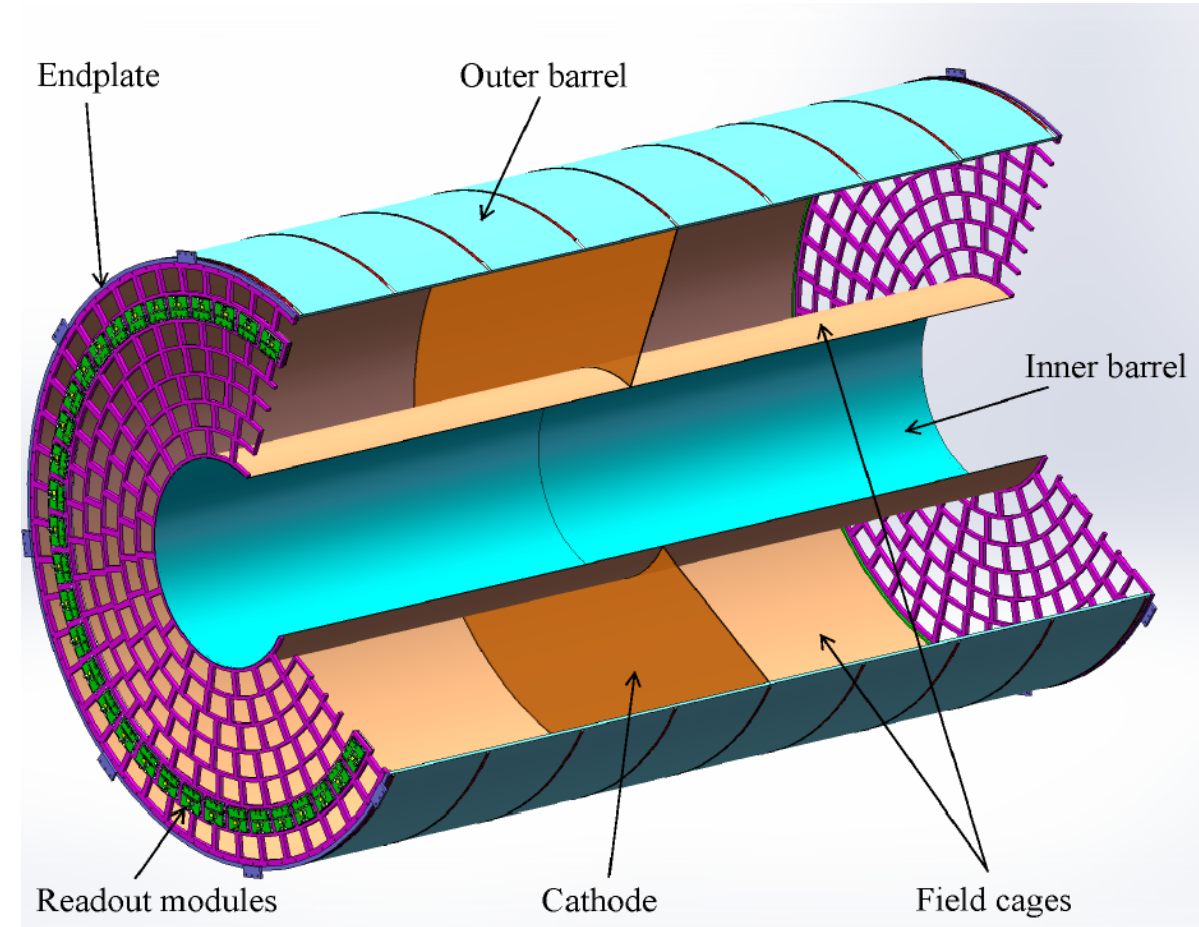
- To meet Low-lumi Z physics
- TPX3 and TPX4
- $\sim 1\text{W}/\text{cm}^2$
- $dN/dx + dE/dx$

- CEPC community initiated the technical comparison and selection, balancing factors including **R&D efforts, detector performance, cost, power consumption and construction risks.**

Parameters of TPC technology in CEPC TDR

- Requirements
 - Momentum resolution (combined with ITK and OTK):
 $2 \times 10^{-5} (\text{GeV}/c)^{-1}$
 - PID (combined with OTK): 3σ separation between π , K , p with momenta up to 20 GeV/c
 - Low material budget
- Overall design
 - A chamber (inner and outer cylinders, endplates) + readout modules
 - Total length: 5.8 m
 - R extension: 0.6 - 1.8 m

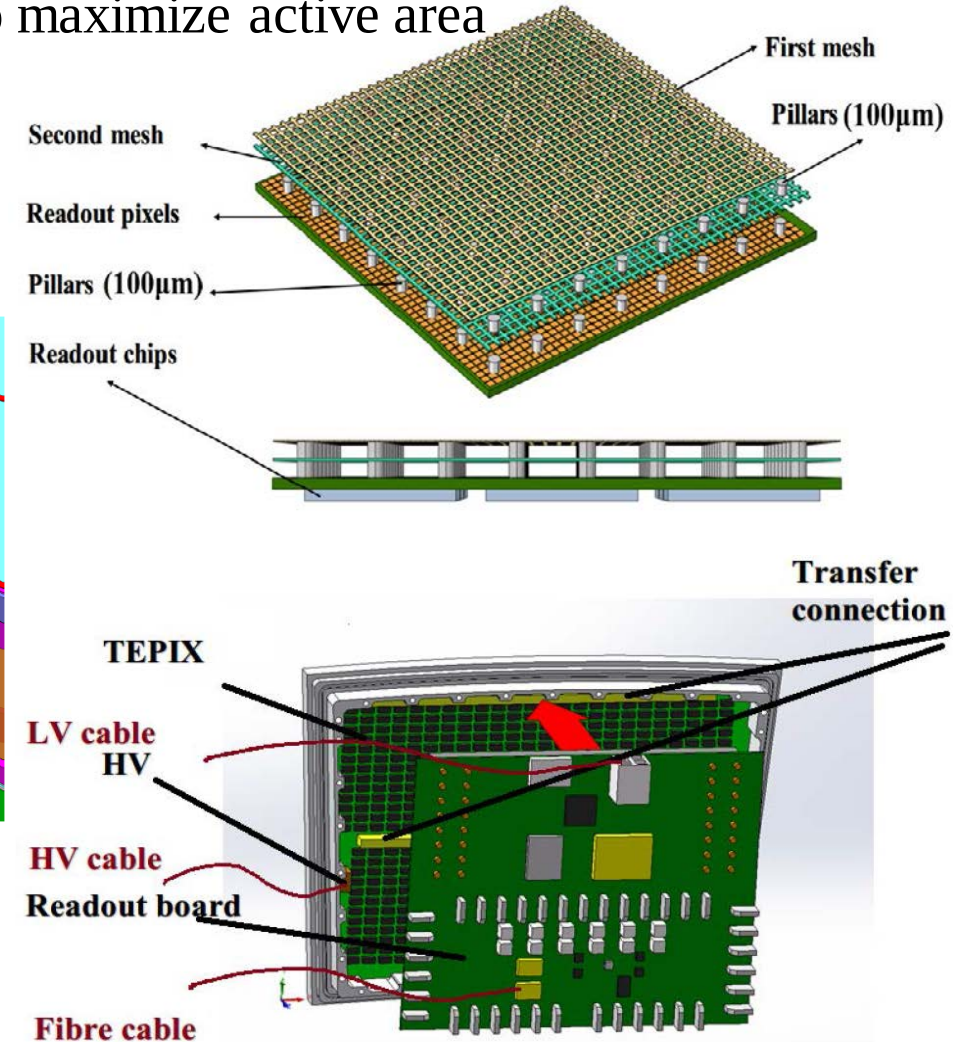
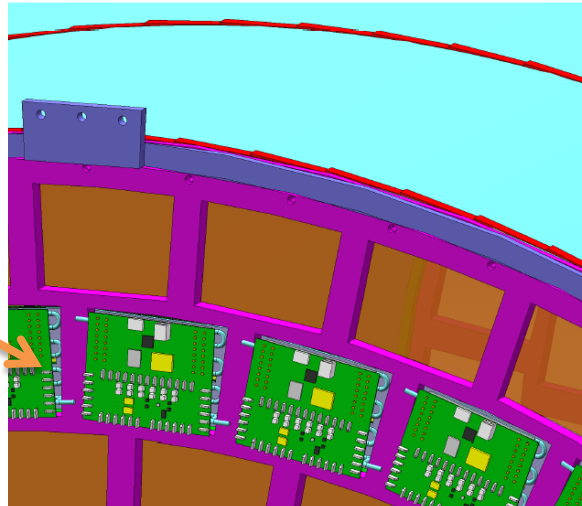
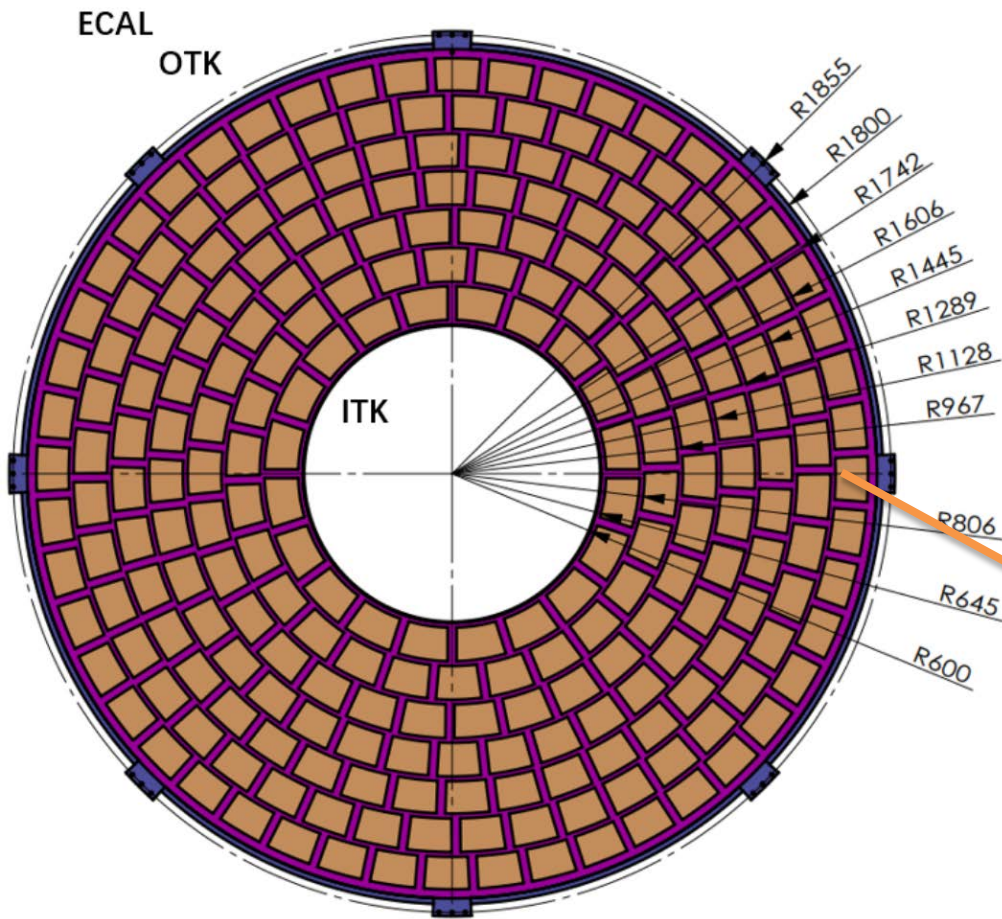
TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Combined Si detector	OTK and ITK silicon trackers
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF ₄ /iC ₄ H ₁₀ =95/3/2
Maximum drift time	34μs @ 2.75m
Detector modules	High granularity readout Micromegas



Detailed design of TPC detector in TDR

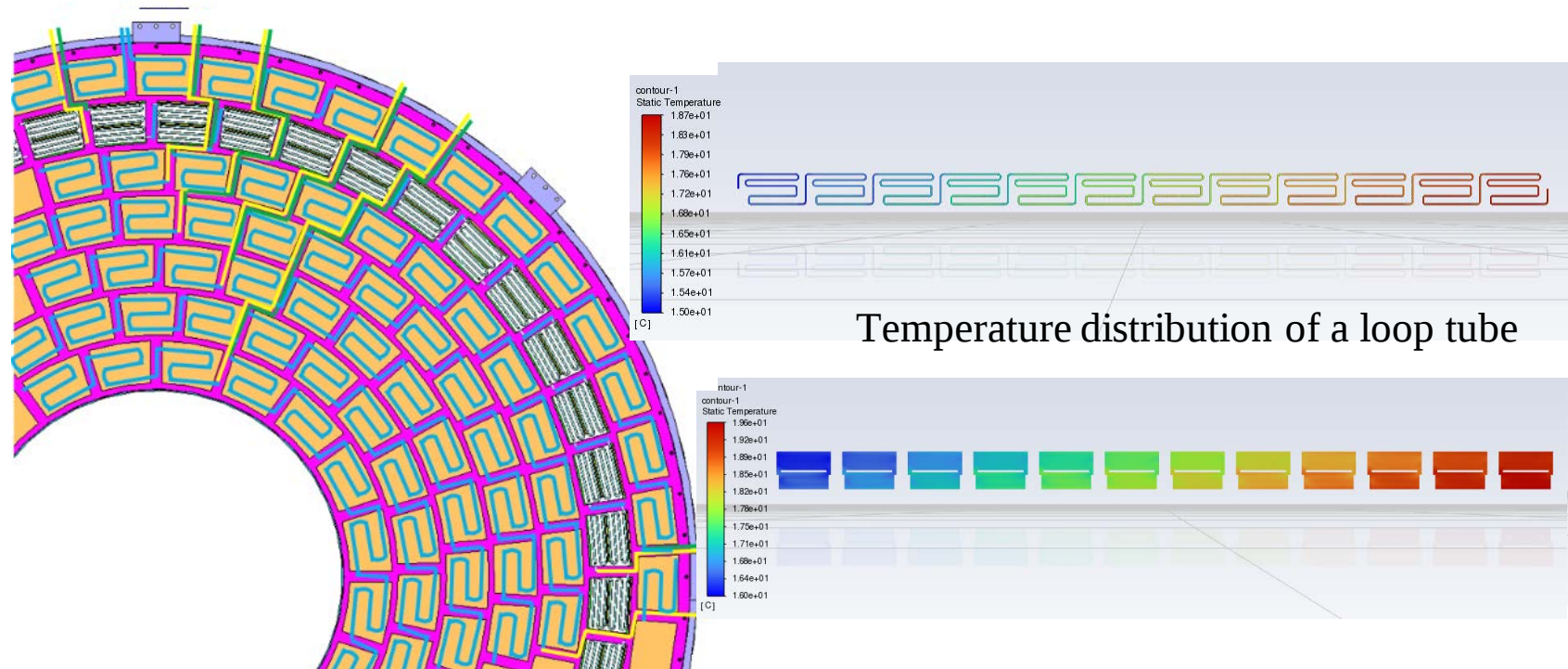
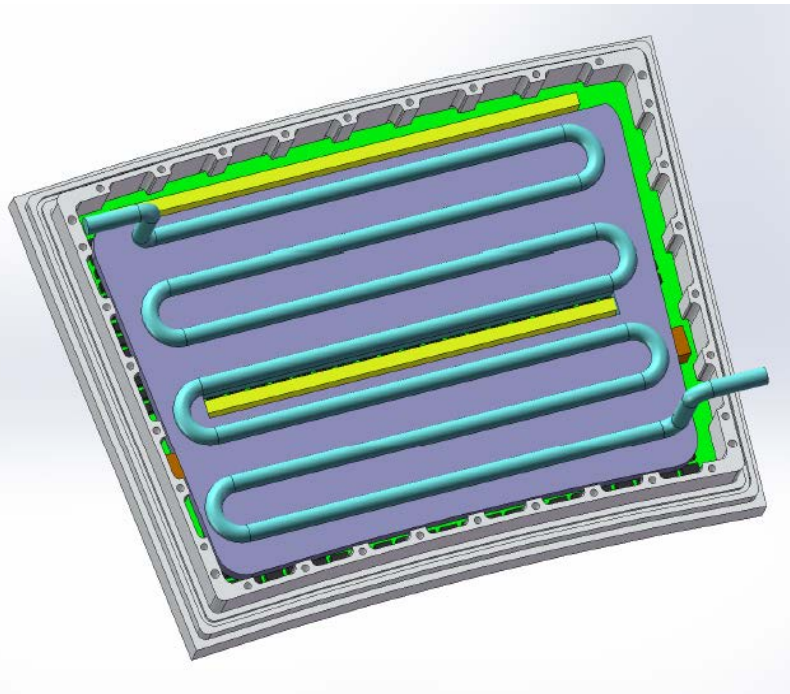
Readout module design

- Readout modules on the endplate
 - 25mm thick aluminum endplate: 7 layers of windows along the radial direction
 - Readout modules with support frame installed in windows to maximize active area



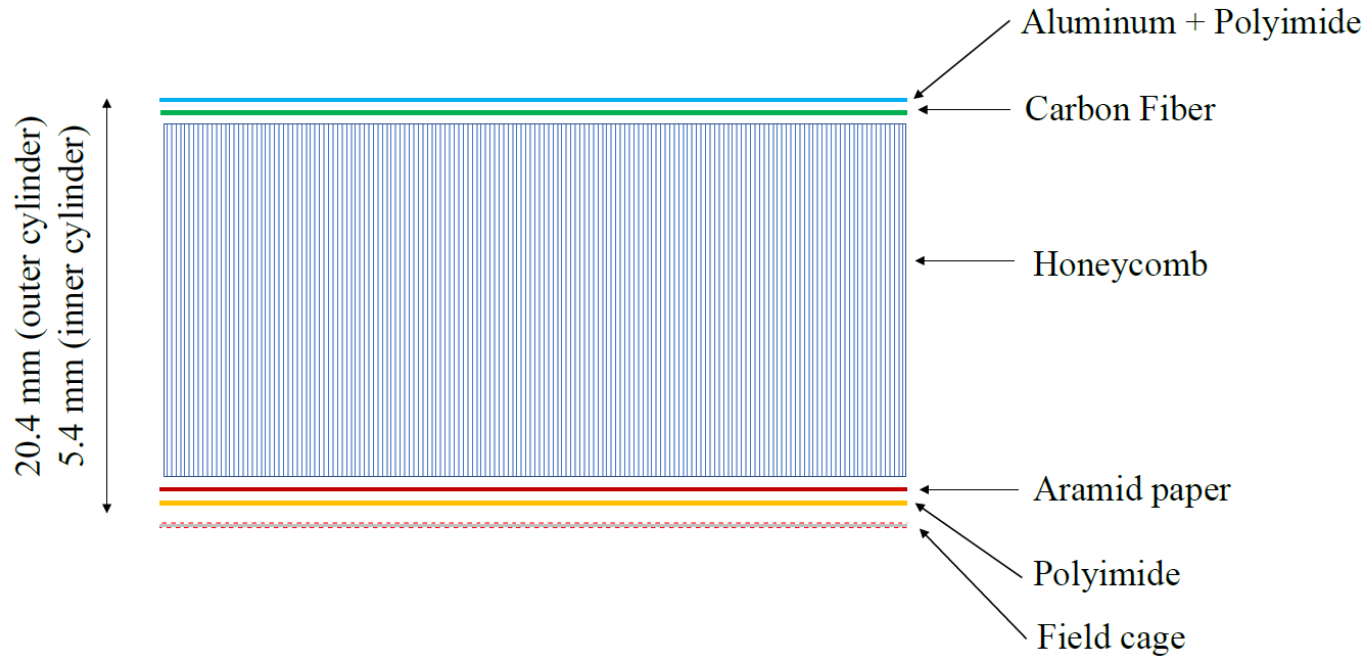
Water cooling design

- Water cooling system and FEA analysis (To meet the power consumption : $100\text{mW}/\text{cm}^2$ - $200\text{mW}/\text{cm}^2$)
 - A water-cooled plate and tubes in each readout module
 - 21 parallel cooling loops in each endplate, each loop is connected in series with 12 readout modules
 - Temperature difference between the outlet and inlet is simulated to be $3.3\text{ }^{\circ}\text{C}$ @ 1.5m/s flow velocity of cooling water through a 6 mm-diameter pipe
 - With an inlet water temperature of $15\text{ }^{\circ}\text{C}$, the highest temperature of the chip is $<20^{\circ}\text{C}$



Light barrel design

- To reduce mechanical deformation, improve insulation performance, and minimize the material budget
 - Sandwich structure
 - Outer cylinder thickness: 20.4mm, Material budget: 0.69% X_0
 - Inner cylinder thickness: 5.4mm, Material budget: 0.45% X_0
 - Sufficient insulation can withstand a voltage of 62kV

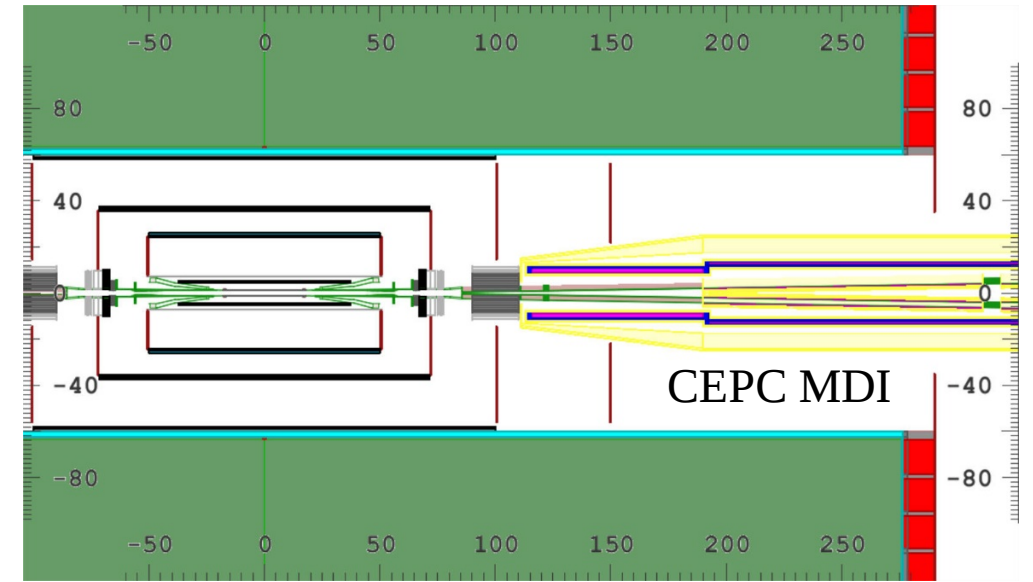


Component	Layers	X [cm]	X_0 [cm]	X/X_0 [%]
TPC outer wall				
Faraday cage shield	Aluminum	0.005	8.9	0.06
Faraday cage shield substrate	Polyimide	0.005	28.6	0.02
Outer wall support cylinder	Carbon fiber	0.02	25.28	0.08
Outer wall support cylinder	Nomex honeycomb	1.96	800	0.25
Outer wall support cylinder	Aramid paper	0.01	35	0.03
Insulating layer	Polyimide	0.01	28.6	0.03
Mirror strips layer	Copper	0.0012×0.95	1.44	0.08
Field cage substrate	Polyimide	0.005	28.6	0.02
Field strips layer	Copper	0.0012×0.95	1.44	0.08
Glue	Epoxy	0.02	35.3	0.06
TPC inner wall				
Field strips layer	Copper layer	0.0012×0.95	1.44	0.08
Field cage substrate	Polyimide	0.005	28.6	0.02
Mirror strips layer	Copper	0.0012×0.95	1.44	0.08
Insulating layer	Polyimide	0.01	28.6	0.03
Inner wall support cylinder	Aramid paper	0.01	35	0.03
Inner wall support cylinder	Nomex honeycomb	0.46	800	0.06
Inner wall support cylinder	Carbon fiber	0.020	25.28	0.08
Faraday cage shield substrate	Polyimide	0.005	28.6	0.02
Faraday cage shield	Aluminum	0.005	8.9	0.06
Glue	Epoxy	0.02	35.3	0.06

- **Simulation and prototype preparation**

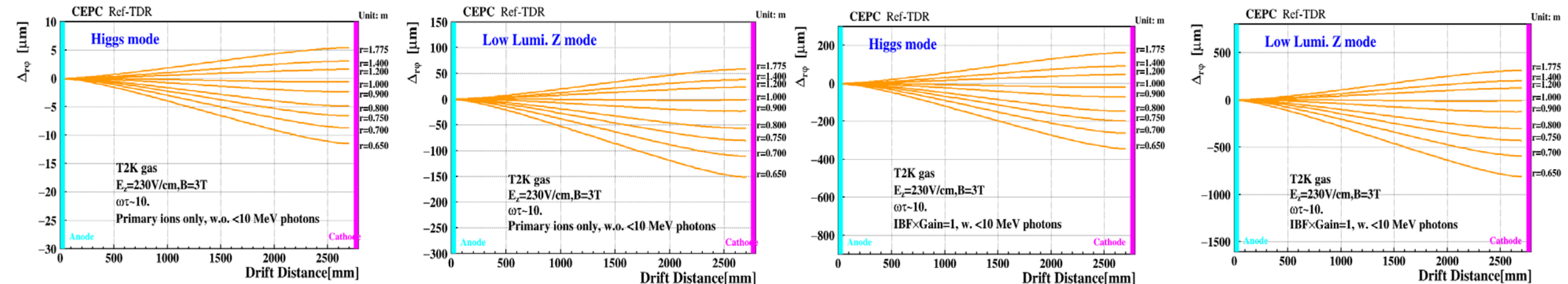
Beam background simulation

- Space charge in TPC chamber
 - Physics events: $H \rightarrow ss/cc/sb$, $Z \rightarrow qq \dots$ (High P_T)
- Low-lumi Z background sources
 - I. Pair production (Luminosity related)
 - II. Single Beam (BGB, BGH, Touschek Scatter...)
 - III. Synchrotron Radiation
 - IV. Injection background
- Estimation of the charge density and distortion



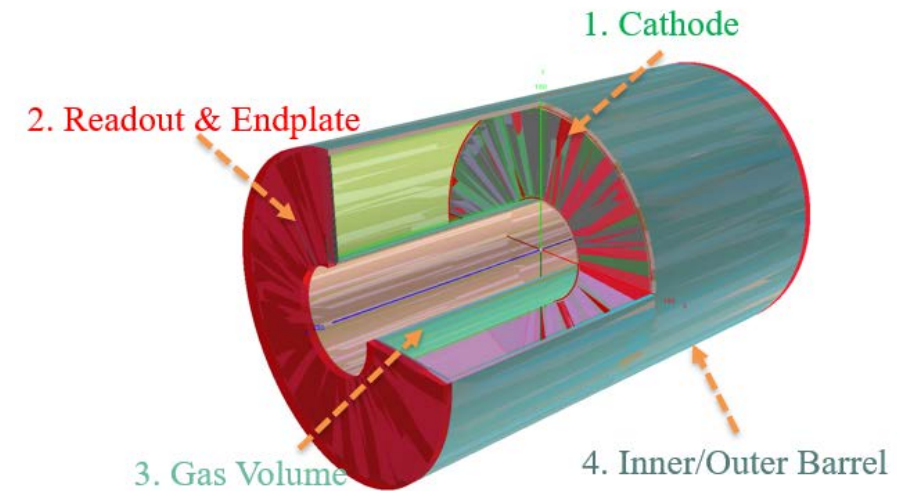
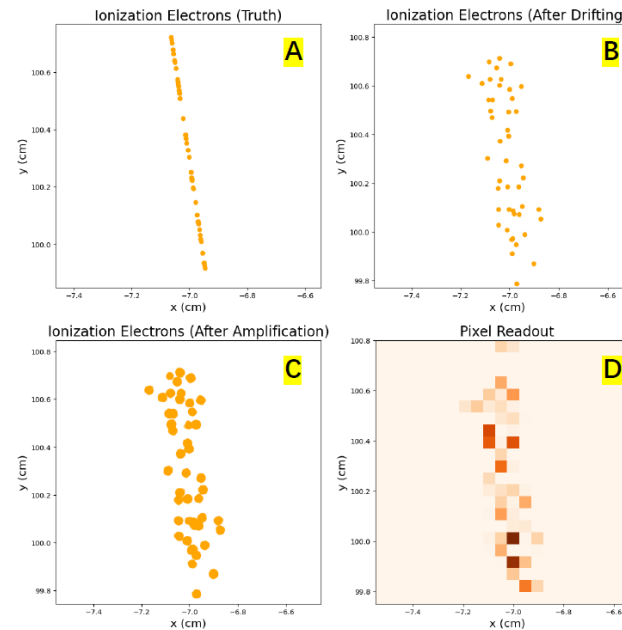
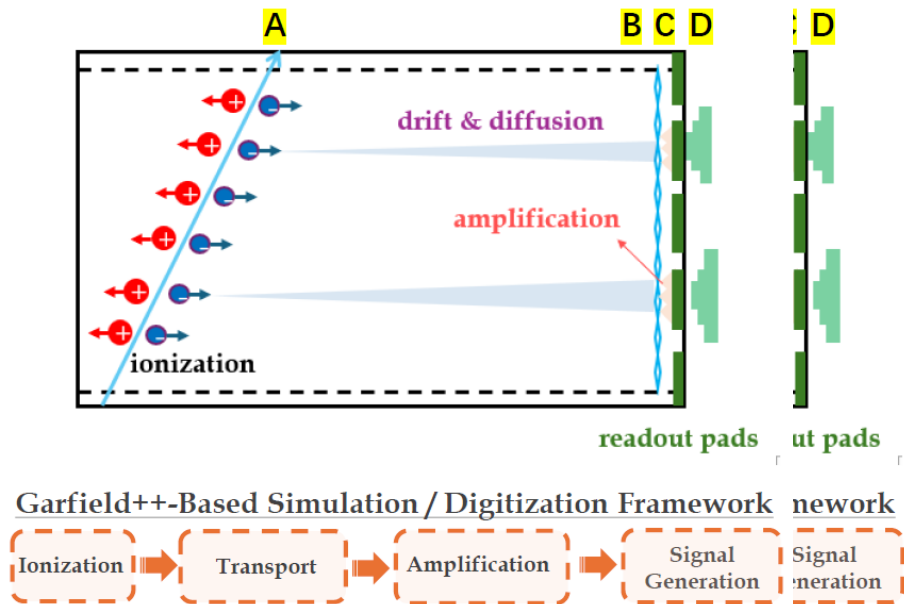
Only primary ions && w.o. low-energy photons and IBF

IBF $\times$ Gain = 1 && w. low-energy photons



Full Simulation of High granularity readout TPC – Framework

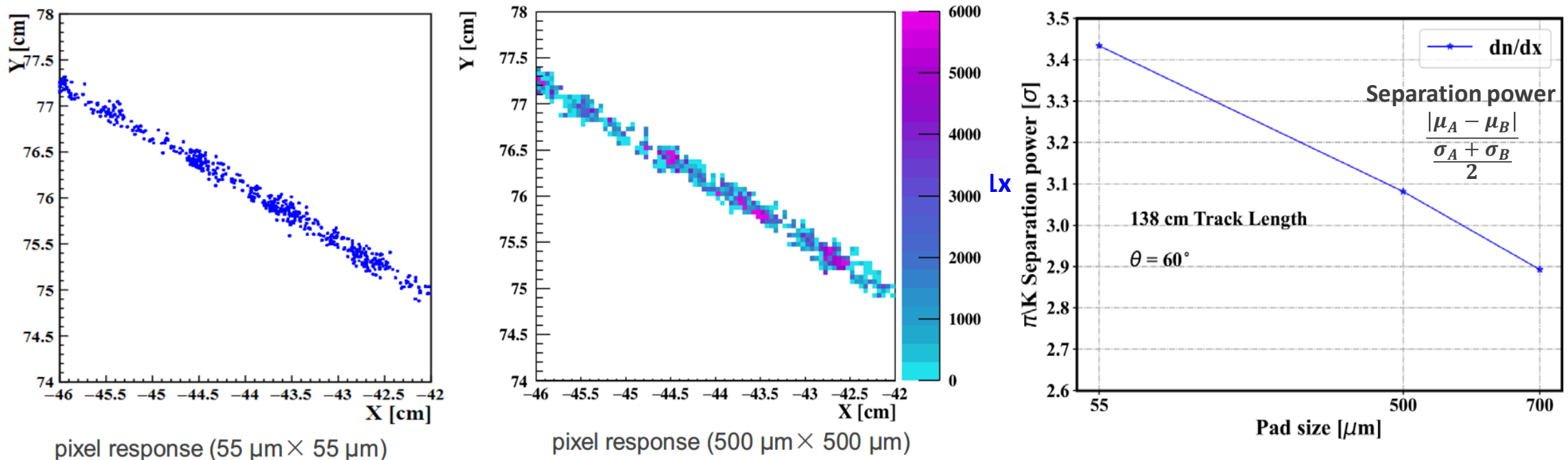
- Sophisticated software for simulation/digitization/reconstruction using Garfield++ and Geant4
 - Geometry implementation based on CEPC TDR
 - Cathode, Micromegas readout and endplate, barrel, gas volume
 - PID with dn/dx
 - Garfield++-based full simulation/digitization
 - Improved reconstruction based on truncated mean of pixels
 - Tracking: Reconstruction with parameterized hit resolutions



Simulation of TPC detector under 3T and T2K mixture gas

Full Simulation of High granularity readout TPC – Readout size

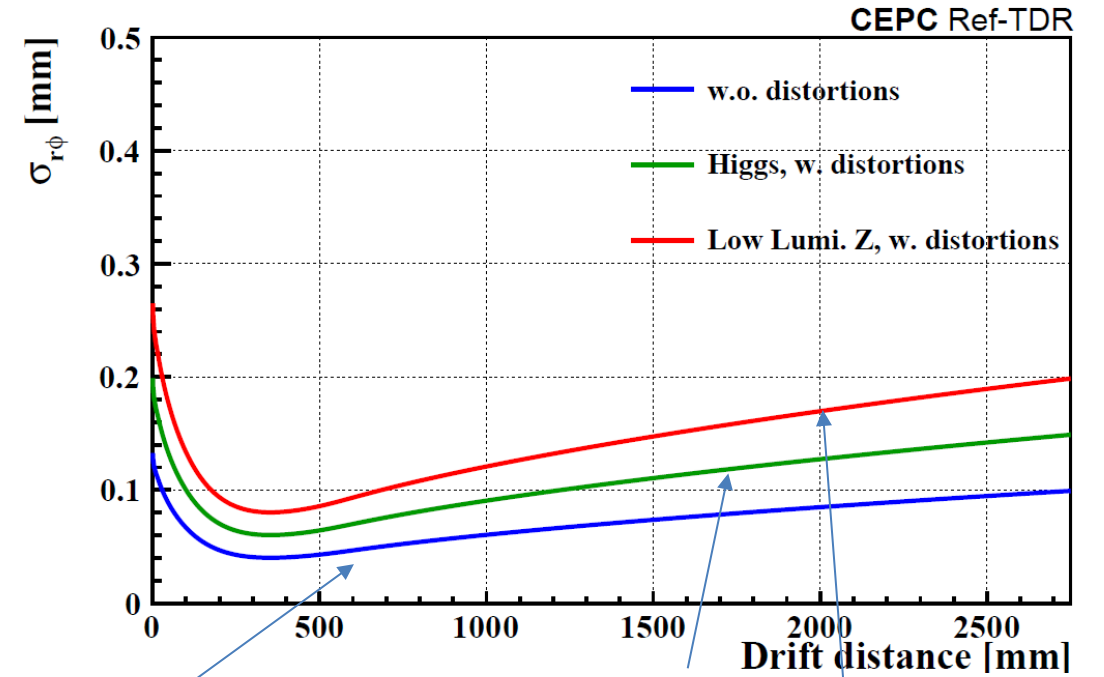
- Simulation results showed that readout size can be optimized at around 500 μm .
 - Optimization started in this TDR to meet Higgs/Z at 3T
 - Focused on **100mW/cm² and 500 μm readout** for TDR (<10kW/endplate, Water cooling option)
- TPX3/4 (55 $\times$ 55 μm^2 , 110 $\times$ 110 μm^2) readout TPC prototype has been validation on DESY beams.
 - Power consumption: 2W/cm²; Low power mode: 1W/cm² (**high power consumption!**)



Optimization of readout size. Balancing of performance and cost power consumption, etc.

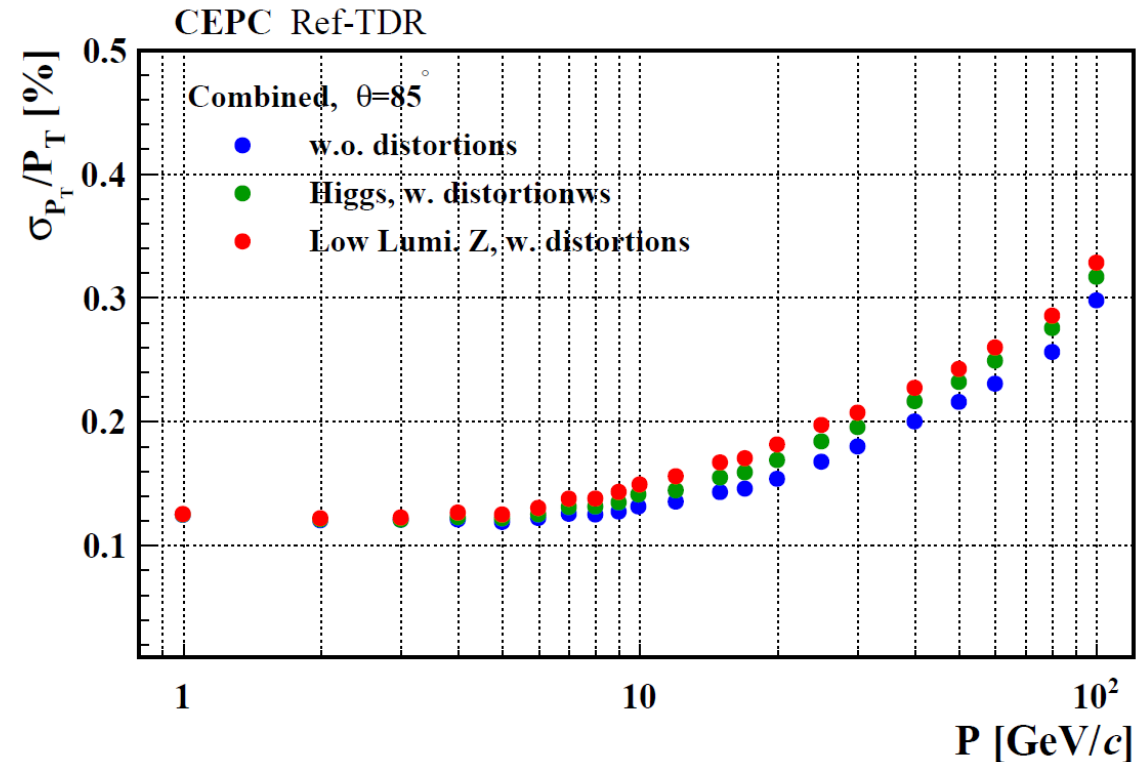
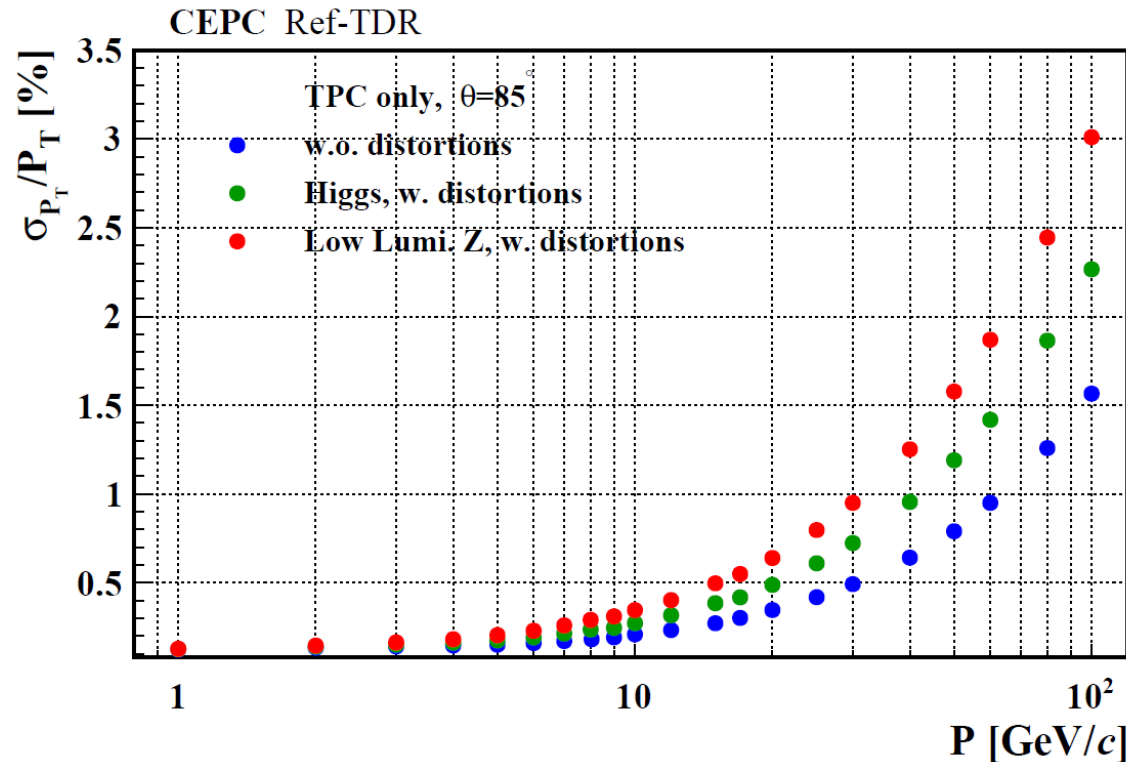
Full Simulation of High granularity readout TPC – Spatial resolution

- Impact of space-point distortions on spatial resolution
 - Space-point distortions can be corrected by the data-driven track-based calibration
 - Error contributions to the calibrated spatial resolution :
 - Space-charge distortion: $< 80\mu\text{m}$ in Higgs, $< 160\mu\text{m}$ in low-lumi. Z, dependent on L_{drift}
 - NUMF effects on the drift process (after correction with magnetic field map): $< 65\mu\text{m}$
 - Mechanical deformation affecting the electric field and drift process : $< 40\mu\text{m}$
- Conservatively estimated, the calibrated spatial resolution degrades by $\sim 50\%$ and 100% at the point with the longest drift distance in Higgs and low-luminosity Z modes respectively.



Full Simulation of High granularity readout TPC - Momentum resolution

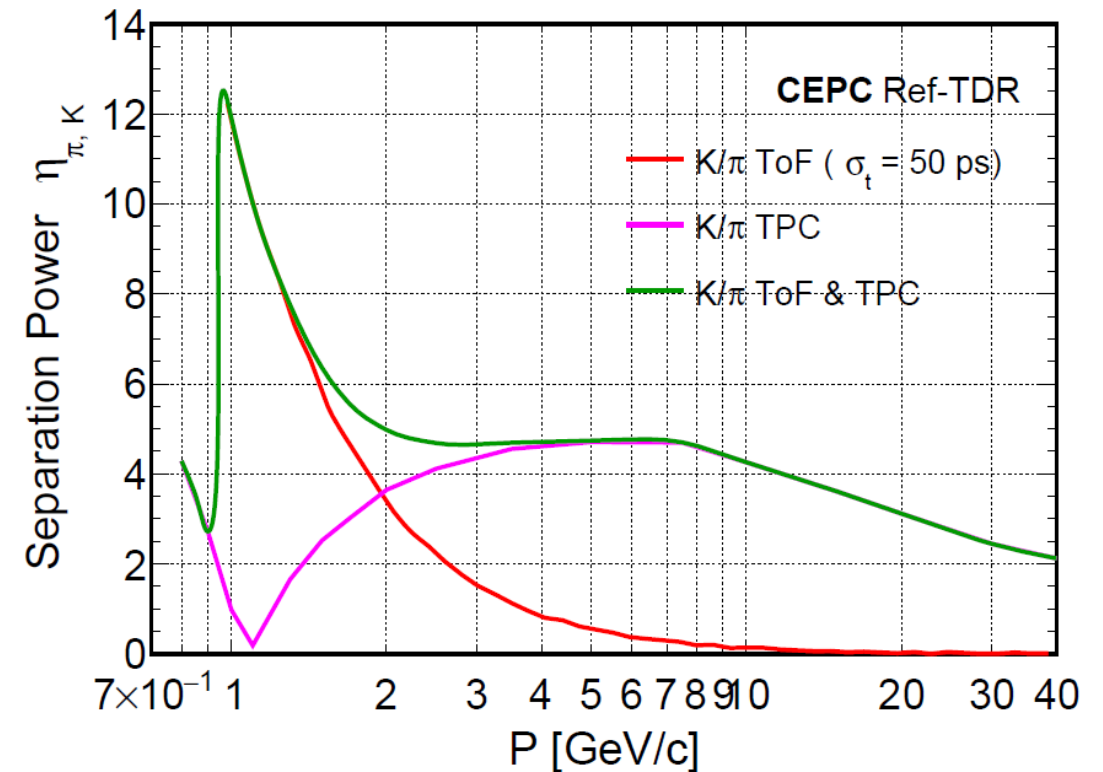
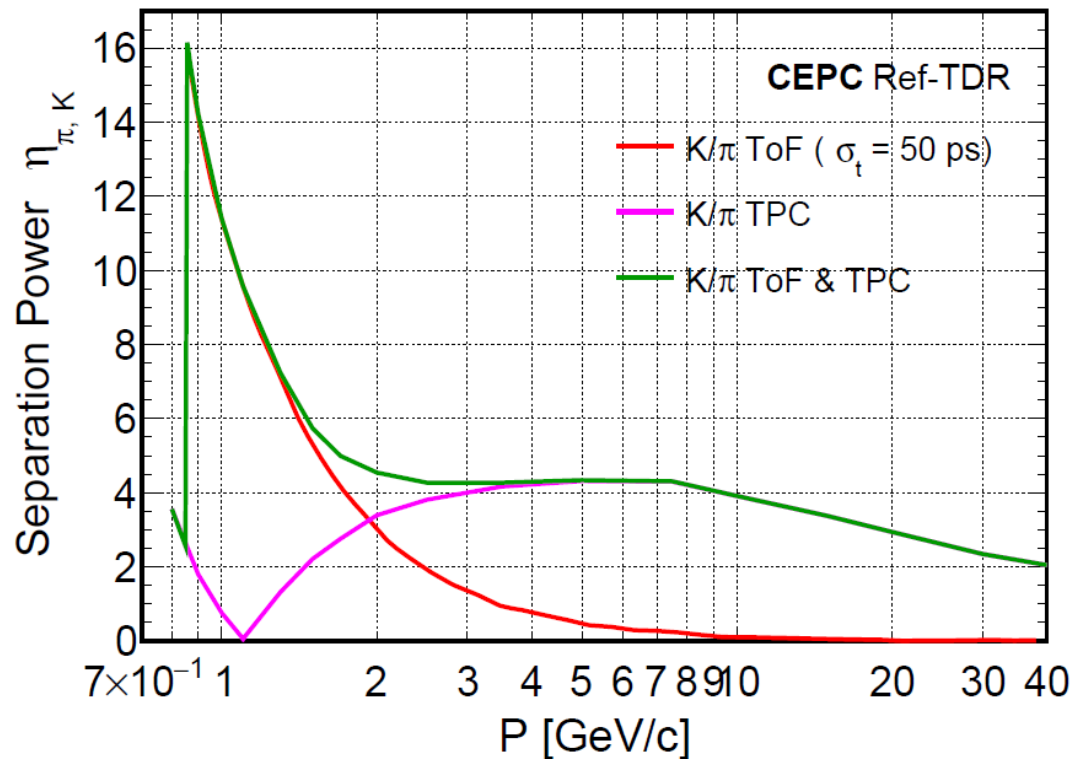
- Momentum resolution
 - Compared to idea scenario, momentum resolution with the TPC standalone degrades, especially high momentum
 - 11% degradation after combining the silicon trackers in low lumi. Z mode
- Further simulation with a complicated model is ongoing.



Full Simulation of High granularity readout TPC – PID performance

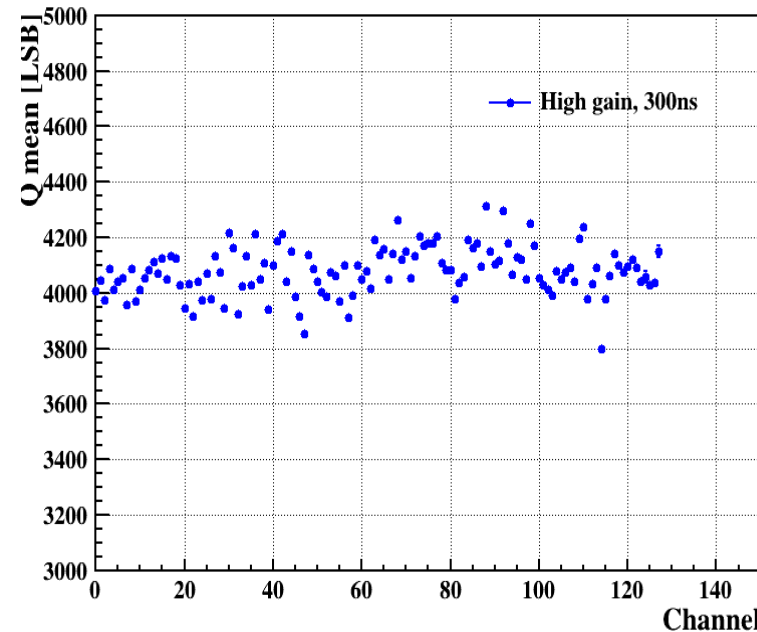
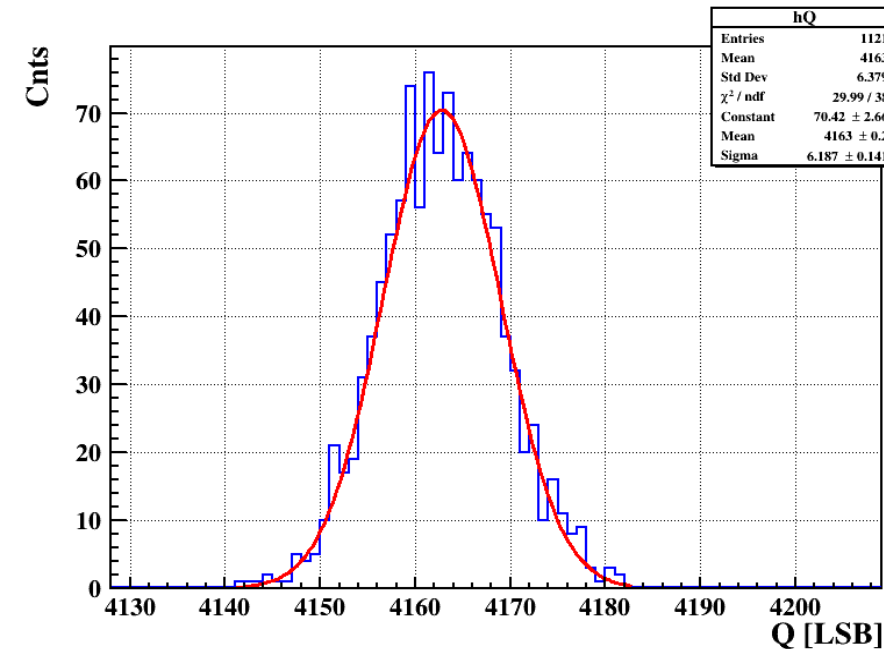
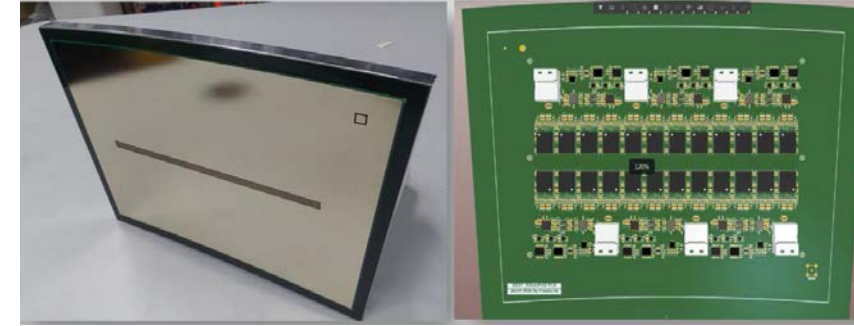
- K/π separation power using the combined information of ToF and TPC
 - ToF information compensates for momentum range of around 1 GeV/c
 - Larger than 3σ separation between K/π with momentum up to 20 GeV/c

$$\eta_{A,B} = \frac{|\mu_A - \mu_B|}{\frac{1}{2}(\sigma_A + \sigma_B)}$$

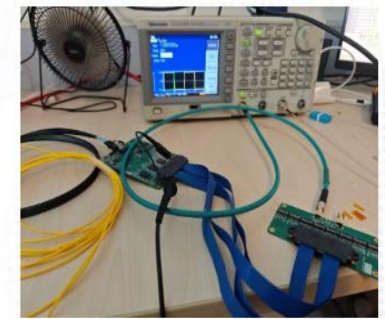


Validation and commissioning of TPC prototype

- R&D on High granularity readout TPC readout for CEPC TDR.
 - ASIC chip developed and **2nd prototype wafer has been done** and tested.
- Energy/Time value of the channels according to the charged injected
 - The uniformity test result of single TEPIX chip : <5%
- A TPC readout module has developed with 10×300 readout channels (24 TEPIX chips) for the beam test with DRD1 collaboration.



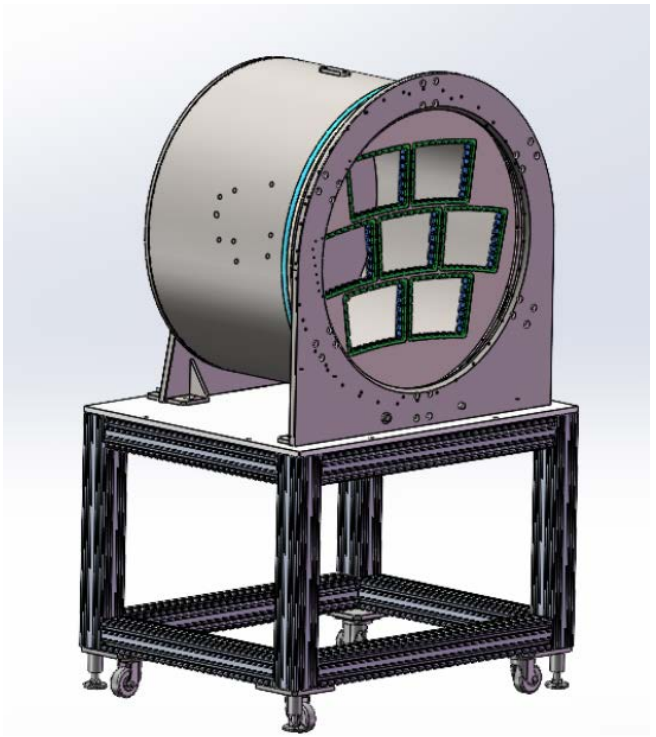
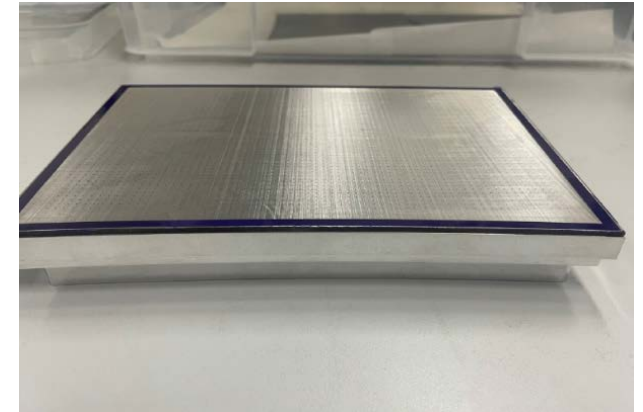
Energy distribution result of TEPIX chip



Work plan of TPC R&D

- Short term work plan (**before TDR**)
 - Optimization of TPC detector for CEPC TDR
 - Prototyping R&D and validation with the test beam
 - mechanics, manufacturing, beam test, full drift length prototype
 - Performance of the simulation and Machine Learning algorithm
- Long term work plan (**next 3-5 years**)
 - Development of TPC prototype with low power consumption FEE
 - Collaboration with LCTPC collaboration on beam test
 - Development of the full drift length prototype
 - Drift velocity. Attachment coefficient, T/L Diffusion, etc.

Milestones achieved	Before TDR	Beyond TDR
Ion backflow suppression	IBF $\times$ Gain < 1 (Gain=2000)	Graphene technology
High granularity readout readout prototype	Validation with beam test	Prototype with Multi-modules
Power consumption ASIC	$\sim 100\text{mW}/\text{cm}^2$ (60nm ASIC)	Optimization readout size
PID resolution	3% (dN/dx)	<3% (dN/dx)
Material budget (barrel)	Carbon Fiber	Full size prototype



Research team

- Core of the research team (**10 staffs + TPC group**)
 - IHEP: **8 staffs + 4 students**
 - Tsinghua: **2 staffs + 3 students**
- Collaboration of the research team (**6 staffs +10 students**)
 - **TPC**: CIAE, Shandong University, Nankai University, Zhengzhou University and Liaoning University
 - **DC**: INFN, Wuhan University, Jilin University
 - **TPC and DC**: DRD1 collaboration and LCTPC collaboration
- Organization of team
 - Collaboration meeting with other international groups



- High granularity readout TPC is chosen as the baseline detector as main track in CEPC TDR. The simulation framework has been developed using Garfield++ and Geant4.
 - Aiming to Higgs and low luminosity Z run at future e+e- collider
 - Radius of TPC from 0.6 m to 1.8 m, readout size $500\mu\text{m} \times 500\mu\text{m}$
 - Ultra light material budget of the barrel and endplate
 - dn/dx has much better PID by getting rid of fluctuations from energy deposition and amplification
 - π/K : $\sim 3\sigma$ @ 20 GeV/c, $\sim 2\sigma$ @ 40 GeV/c
 - Beam-induced backgrounds studied based on Garfield++ and CEPCSW
 - Some validation of TPC prototype have been studies using TEPIX
- All inputs to reference detector TDR, planning the short and long term R&D activates
- Synergies with CEPC and FCCee allow us to continue R&D and ongoing. Team actively involved in the international collaborations.

Many thanks!