Status of TPC for CEPC Physics and Detector TDR

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Content

- Status of CEPC TDR
- Motivation and physics requirements
- Technology survey and choices
- Some progress towards TDR
- Summary

Status of CEPC TDR

- CEPC TDR defined as a CEPC reference TDR (CEPC ref-TDR)
- First IDAC international review
  - Date: 21-22, October, 2024 at IHEP in Beijing
  - 11 experts in the field of HEP detectors (CERN, DESY, Edinburgh, CEA-Saclay, PSI,…)
    - Maxim will join this review meeting
  - PPT presentation: Just covering the chapters by the person in charge
- Some next steps
  - The TDR document draft versions V0 : before 30, December.
  - Second IDAC international review: January, 2025 in Hongkong (HKUST)
  - The TDR document draft versions V1 : before 28, February.
  - The TDR document will be released in June, 2025.

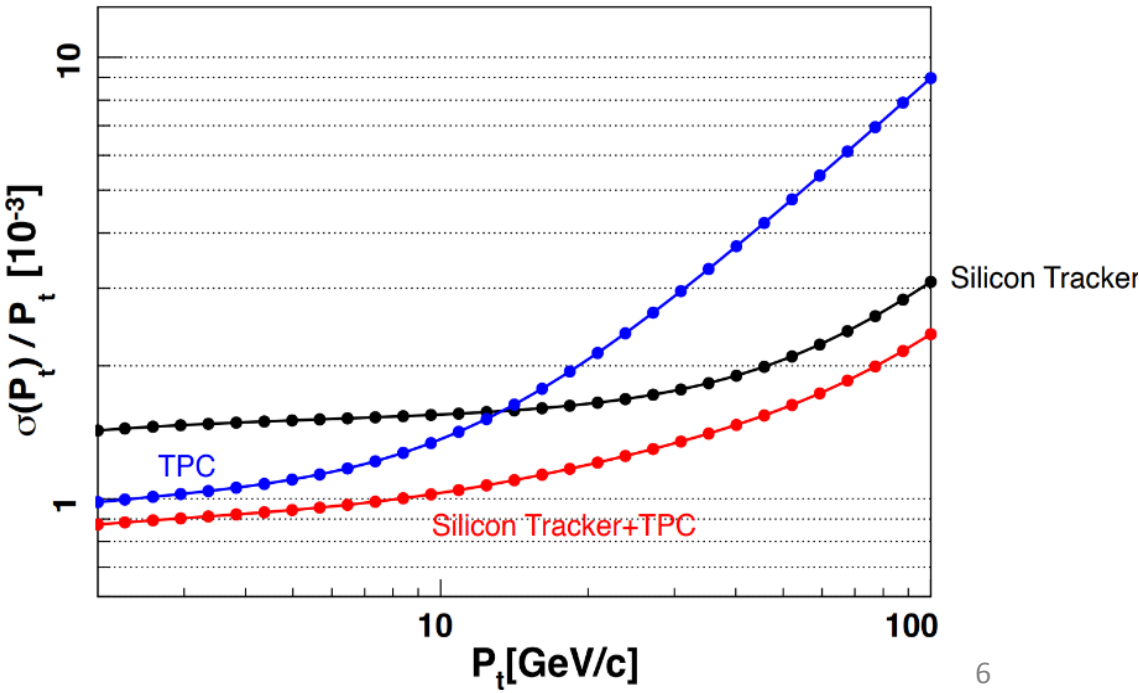
Status of CEPC TDR

- This talk relates to the CEPC Physics and Detector Ref-TDR.
  - Chapter 5: Gaseous tracker
  - Draft of content listed →

Physics requirement

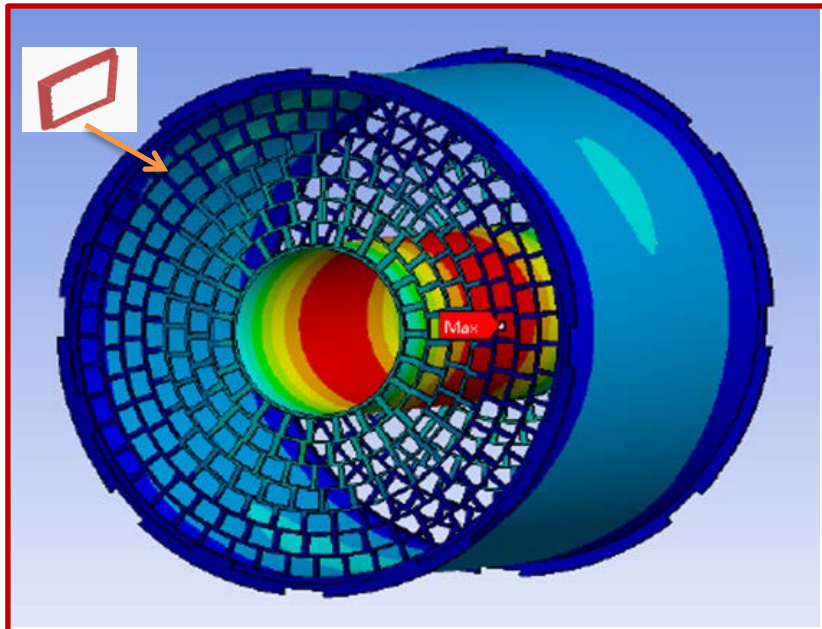
- CEPC operation stages in TDR: **10-years Higgs → 2-years Z pole → 1-year W**
- Phys. Requirements of the track detector
  - Thousands of hits with high spatial resolution compatible with PFA algorithm (low X_0)
- Beneficial for jet & differential at higher energy
  - Highly requirements for excellent JOI & PID resolution (in Jets)：Provide dE/dx + dN/dx ~ 2-3%
  - BMR < 4% & pursue 3%

Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu$m, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\mathrm{GeV}^{-1})$
TPC/Drift Chamber	Precise dE/dx (dN/dx) measurement	Relative uncertainty 3%
Time of Flight detector	Large-area silicon timing detector	$\sigma(t) \sim 30$ ps
Electromagnetic Calorimeter	High granularity	EM energy resolution $\sim 3\%/\sqrt{E(\mathrm{GeV})}$
	4D crystal calorimeter	Granularity $\sim 2 \times 2 \times 2\ \mathrm{cm}^3$
Magnet system	Ultra-thin	Magnet field $2-3$ T
	High temperature	Material budget $< 1.5X_0$
	Superconducting magnet	Thickness < 150 mm
Hadron calorimeter	Scintillating glass	Support PFA jet reconstruction
	Hadron calorimeter	Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(\mathrm{GeV})}$
		Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(\mathrm{GeV})}$

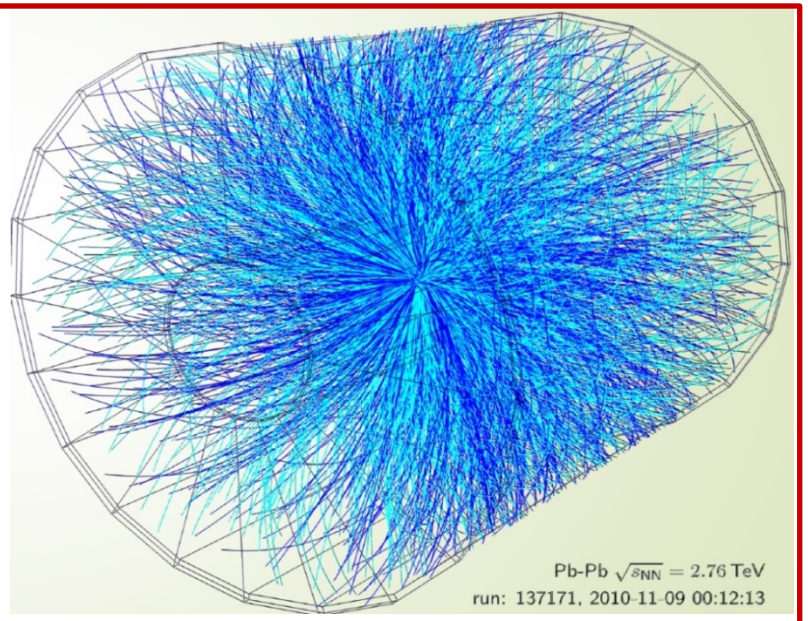


Technology survey and our choices

- 3D high precision resolution track reconstruction with the Ultra light material budget
  - High precision resolution (~**100 μm**) with thousands hits per track
  - High momentum resolution (~**10^{-4} GeV/c**) and High capabilities for **Particle Identification** (~**3%**)
  - Utilize the timing of drift in the z-direction (**nano-second**)
  - A magnetic field parallel to the electric field direction (**Higgs: 3T, Tera-Z: 2T**)
  - Easily installation and replacement modular design
- Considering the technical challenges, performance, risk of detector construction



Modular design

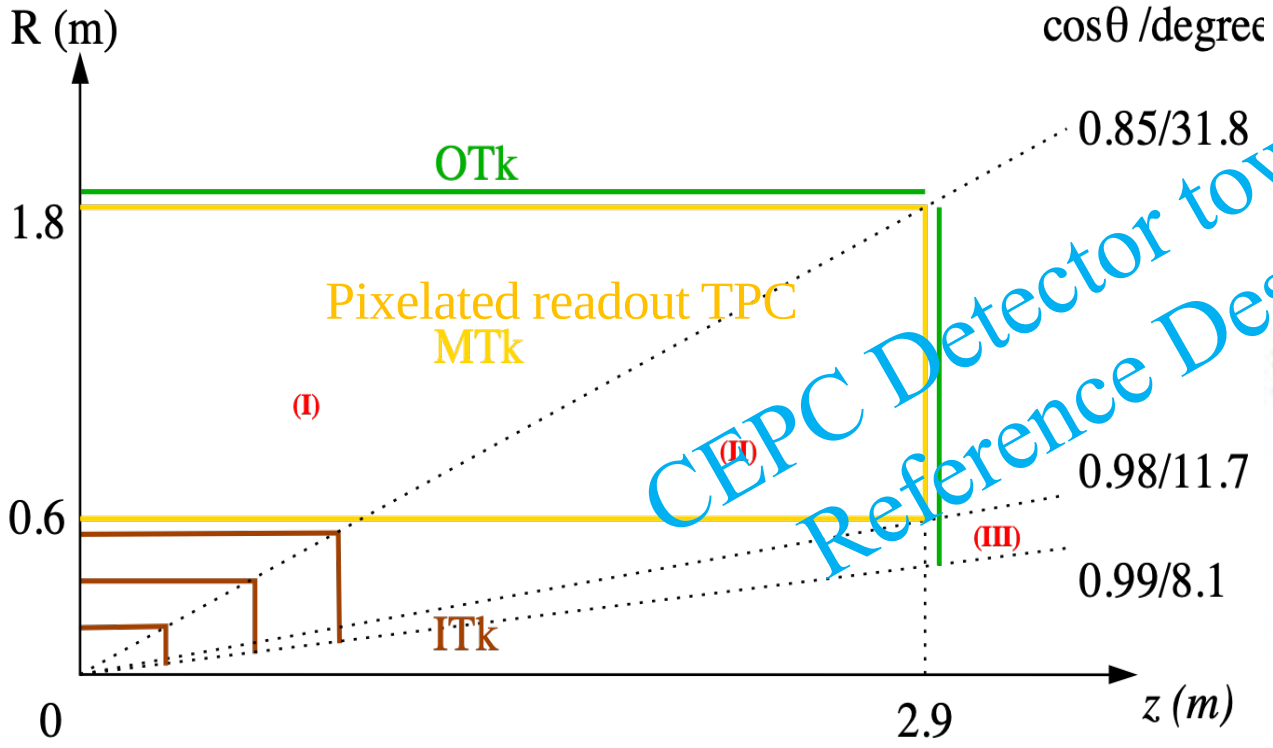


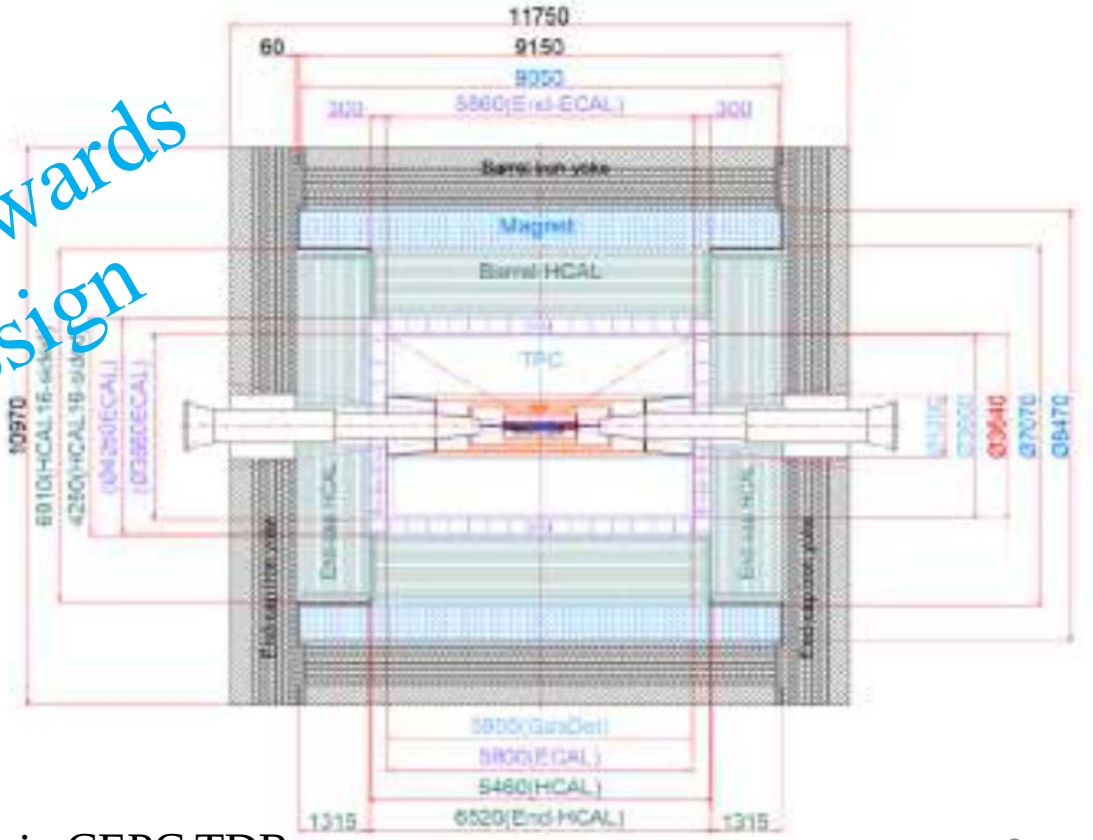
Time Projection Chamber

Drift Chamber

Baseline track detector: Pixelated TPC

- The track detector system: Silicon combined with gaseous chamber as the tracker and PID
  - Pixelated readout TPC is as the **baseline track detector** in CEPC ref-TDR.
    - Pixelated readout TPC as the **main track (MTK)** from radius of 0.6m to 1.8m
  - DC is as the **alternative** track detector at Tera-Z.





CEPC Detector towards Reference Design

Geometry of the track detector system in CEPC TDR

Technical challenges and R&D efforts

Main Technical Challenges

- **Pixelated readout TPC (Baseline)**

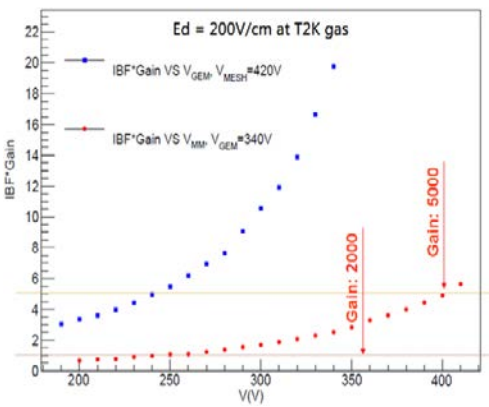
Critical key issues

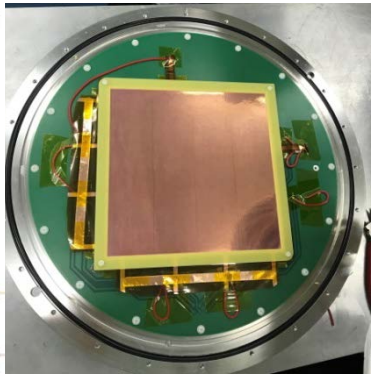
  - **Material budget at endcape/barrel √**
  - **Occupancy and hit density at Tera-Z √**
  - **Ion backflow suppression √**
  - **Running at 2 Tesla √**
  - **Improved PID √**
  - **Reasonable channels(ongoing)**
  - **Reasonable power consumption (ongoing)**

- **DC (Alternative at Tera-Z)**
  - **dN/dx for PID √**
  - **Risk the 5.8m wires and tension (ongoing)**

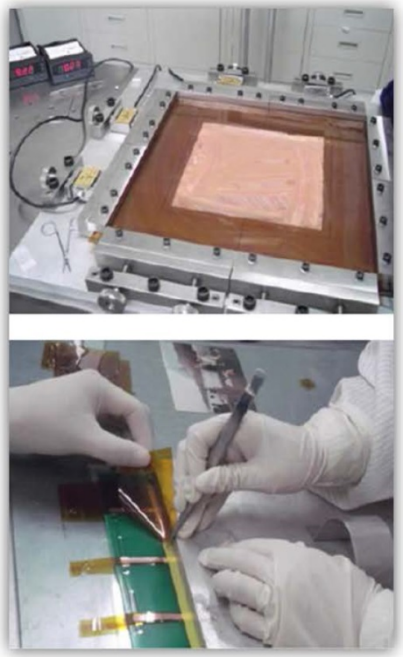
TPC prototype R&D efforts and results

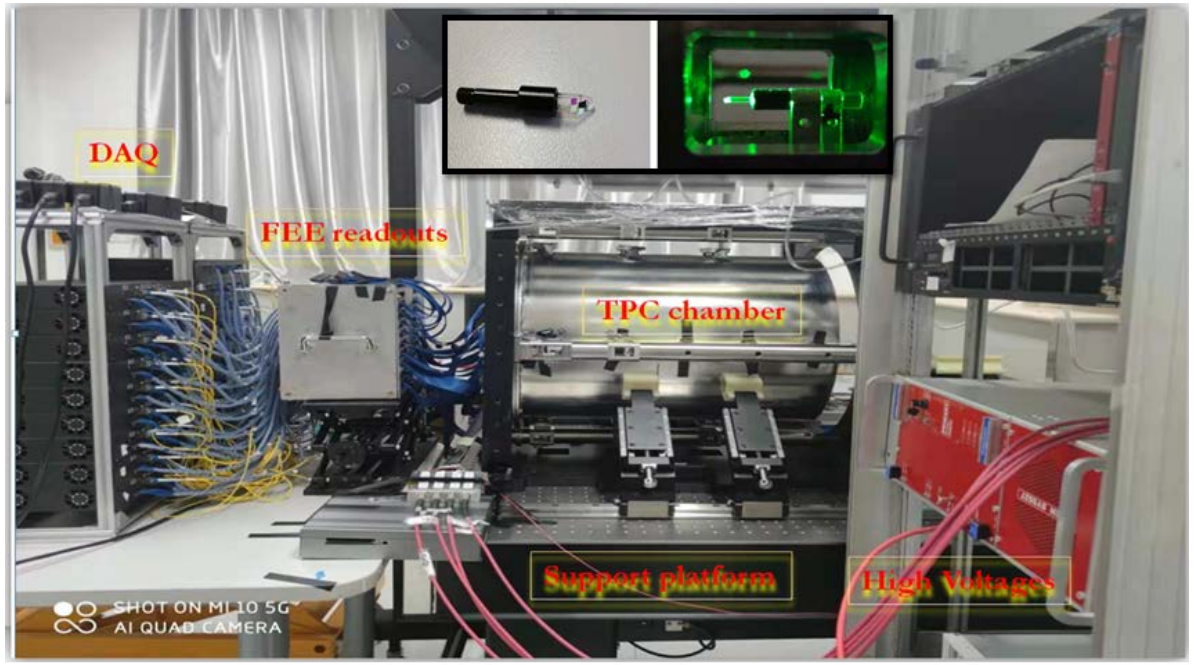
- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to **TPC prototype R&D for Higgs and Tera-Z**
- **Achievement by far:**
  - **IBF×Gain ~1 @ G=2000** validation with hybrid TPC module
  - Spatial resolution of **$\sigma_{r\varphi}$≤100 μm and dE/dx resolution of 3.6%**
  - FEE chip: reach ~**3.0mW/ch with ADC** and the pixelated readout R&D



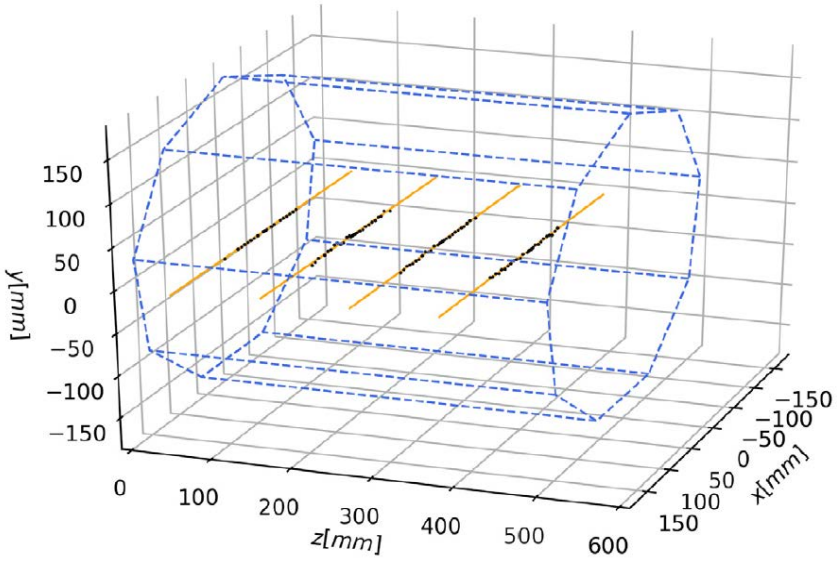


Ion suppression TPC module R&D





TPC prototype with integrated 266nm UV laser



Tracks reconstruction

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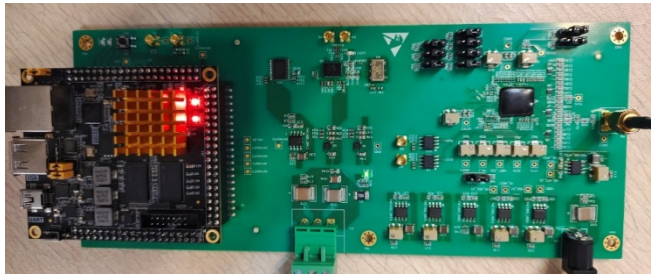
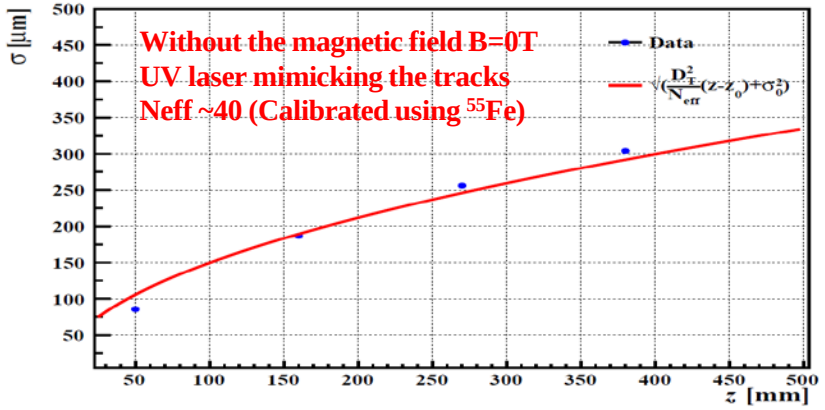
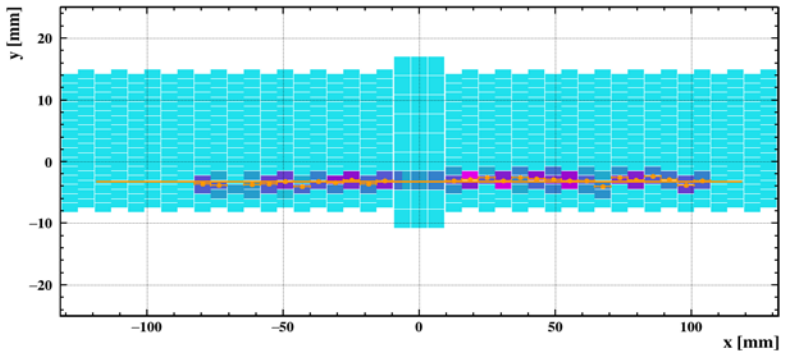
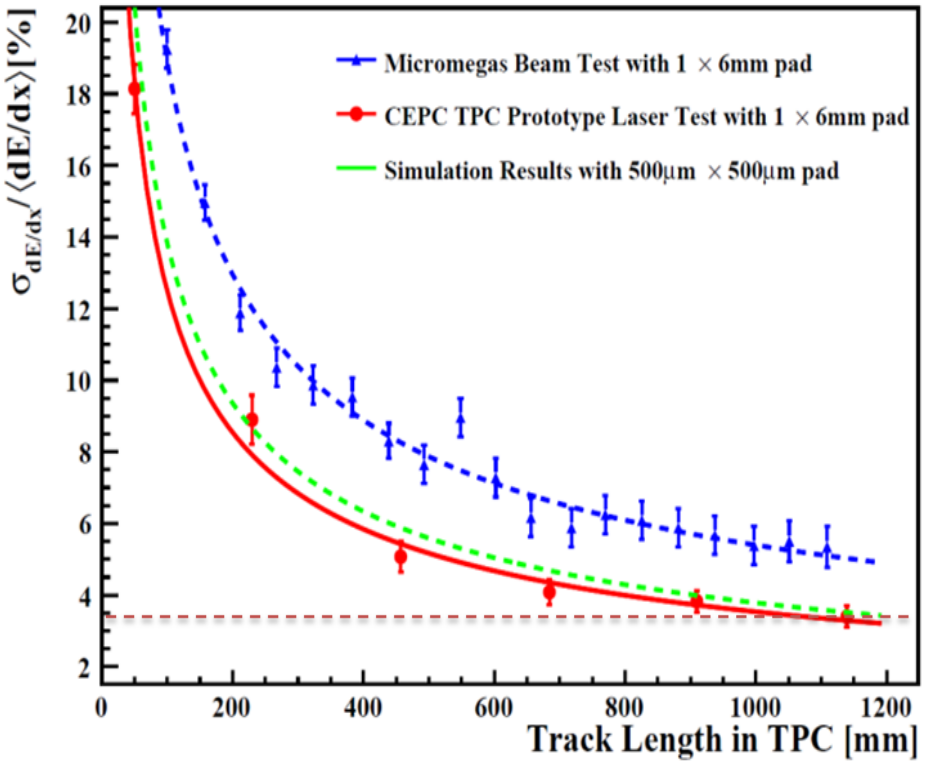
Highlights of TPC prototype R&D

- **Highlights of CEPC pad readout TPC R&D and toward the pixelated readout TPC**
  - Massive production and assemble MPGD lab has been setup at IHEP
  - TPC prototype integrated 266nm UV laser tracks has been studied and analyzed the UV laser signal, all are pretty good to Higgs run.
  - **Easy-to-install modular design** of Pixelated readout TPC for CEPC TDR









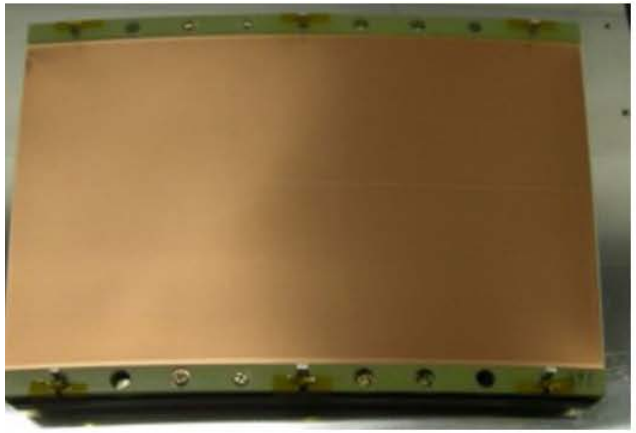
Publications by CEPC TPC group in 2018-2024:

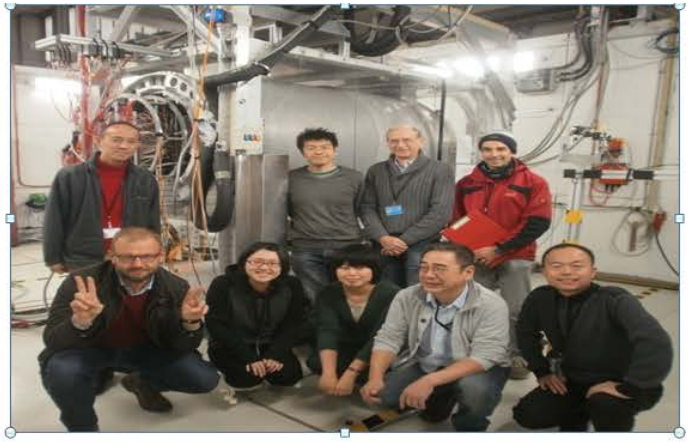
- https://doi.org/10.1088/1748-0221/18/08/E08002
- https://doi.org/10.22323/1.449.0553
- https://doi.org/10.1016/j.nima.2022.167241
- https://doi.org/10.1109/NSS/MIC44867.2021.9875566
- https://doi.org/10.1109/NSS/MIC44845.2022.10399097
- https://doi.org/10.1088/1748-0221/15/09/C09065
- https://doi.org/10.1088/1748-0221/15/05/P05005
- https://dx.doi.org/10.1142/S0217751X20410146
  https://doi.org/10.1088/1674-1137/41/5/056003
- https://doi.org/10.1088/1748-0221/15/02/T02001
- https://doi.org/10.1088/1748-0221/12/07/P07005

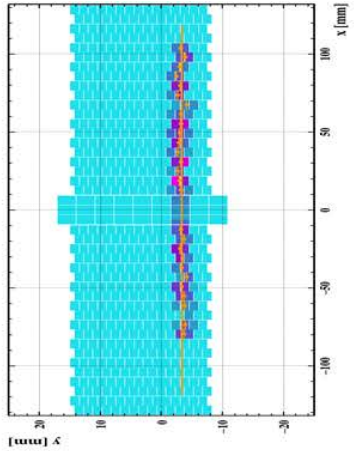
Activity international collaboration

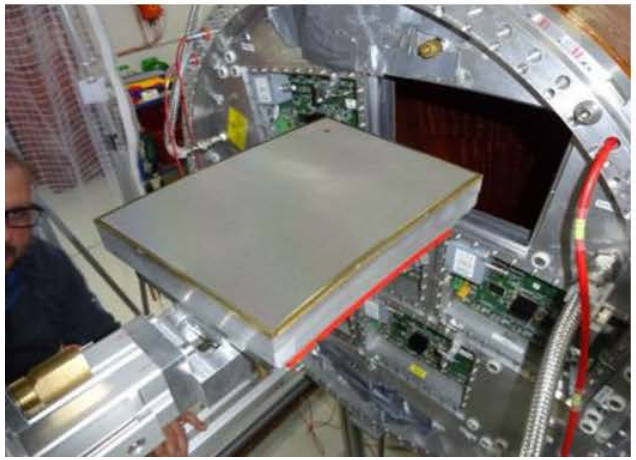
- **Activity collaboration:** Pixelated readout and Pad readout from IHEP and LCTPC collaboration
  - Large Prototype setup have been built to compare different detector readouts for Tera-Z
  - PCMAG: B < 1.0T, bore Ø: 85cm, Spatial resolution of $\sigma_{r\phi} \leq 100$ μm
  - Collaboration implement improvements in **a pixelated readout TPC for CEPC TDR**

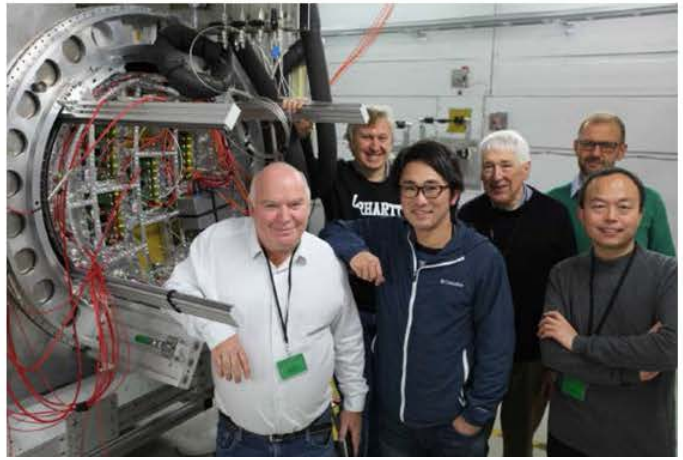
ArXiv. (2023)2006.08562
NIM A (2022) 167241
ArXiv (2022)2006.085
JINST 16 (2021) P10023
JINST 5 (2010) P10011
NIM A608 (2009) 390-396

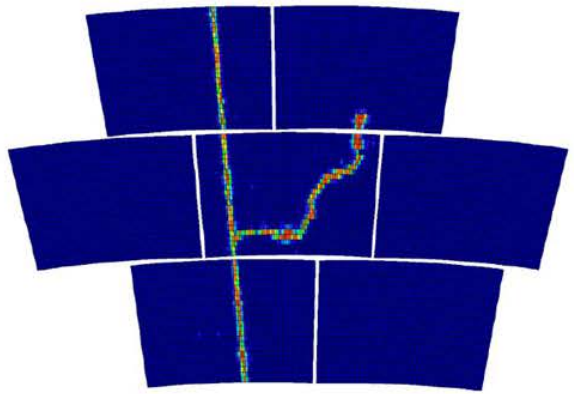










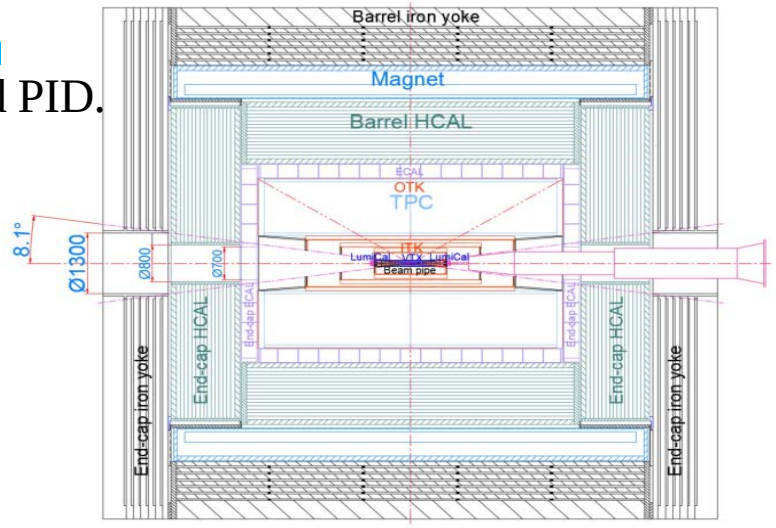


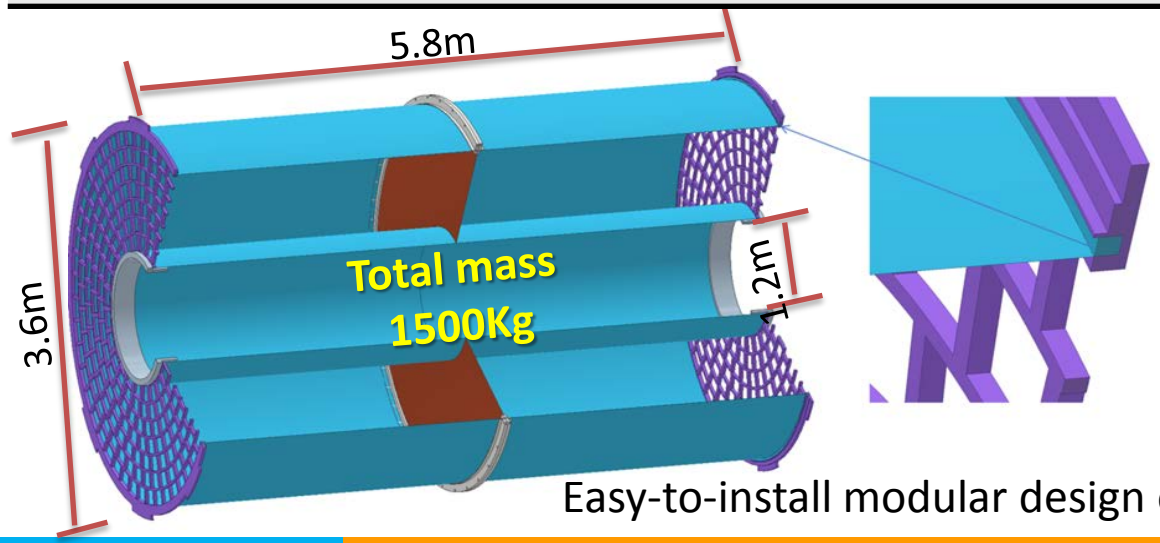
Detailed design and performance of Baseline: TPC

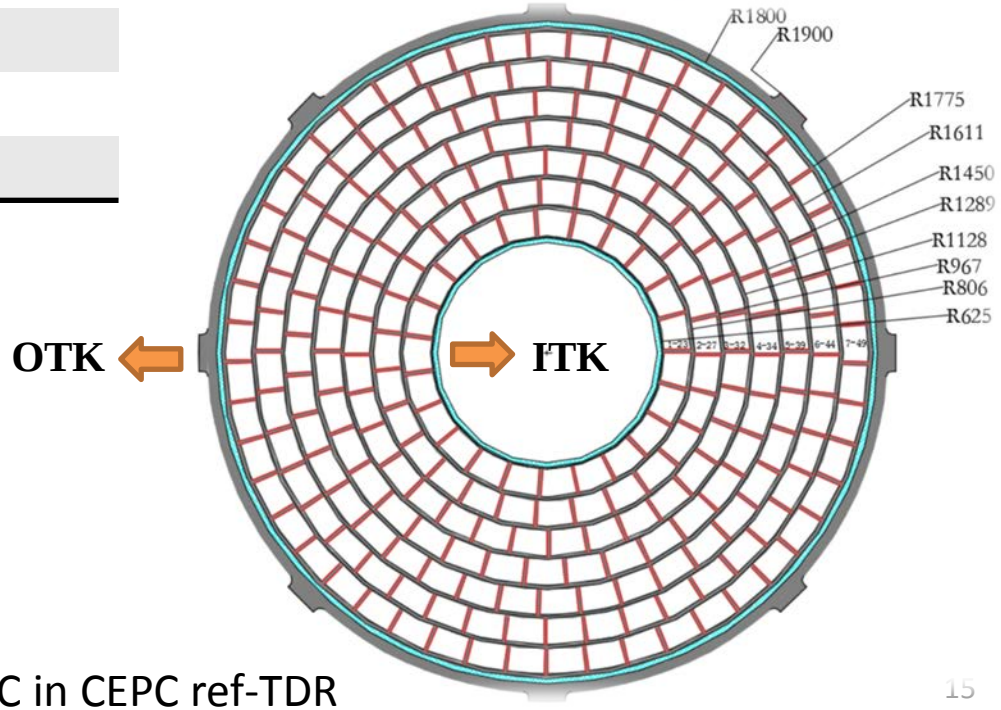
Detailed design of mechanics

- Track detector system: **Silicon combined with gaseous detector** as the tracker and PID.
  - Pixelated readout TPC is as the baseline track detector in CEPC ref-TDR.

TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Module size	206mm×224mm×161mm
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Voltage of Cathode	- 62,000 V
Operation gases	T2K: Ar/CF4/iC4H10=95/3/2
Total drift time	34μs @ 2.75m
Detector modules	Pixelated Micromegas



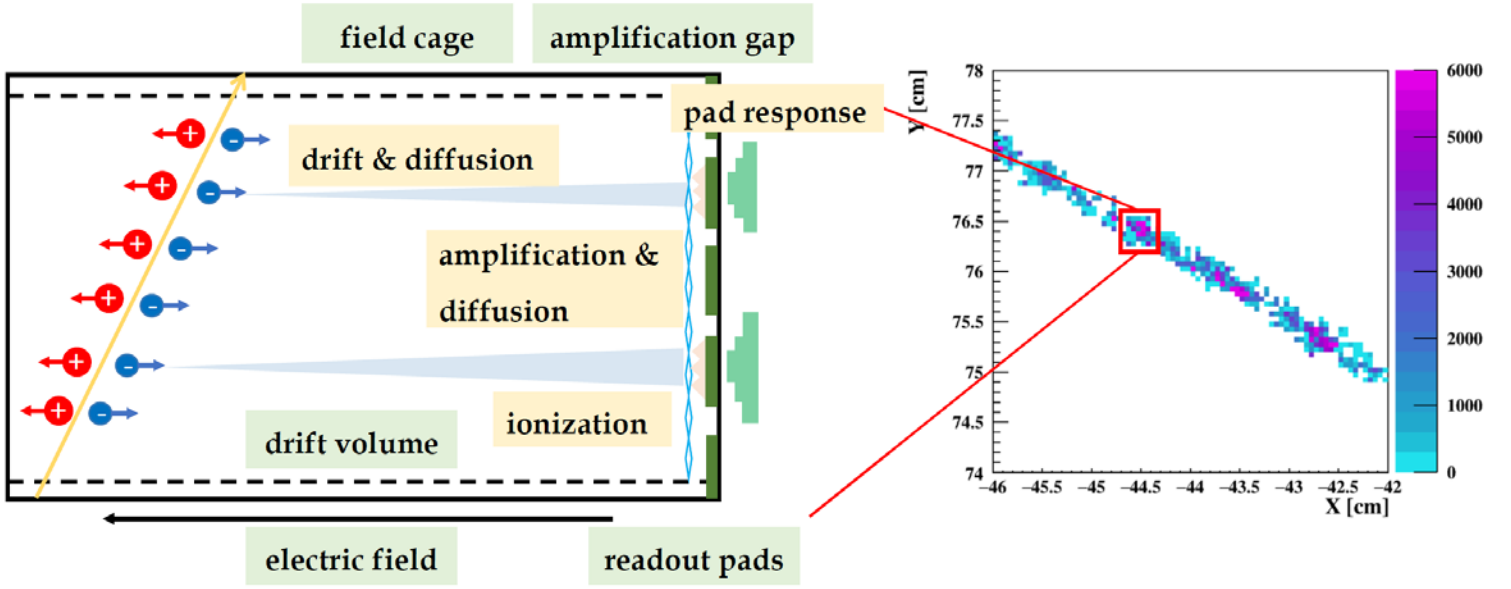


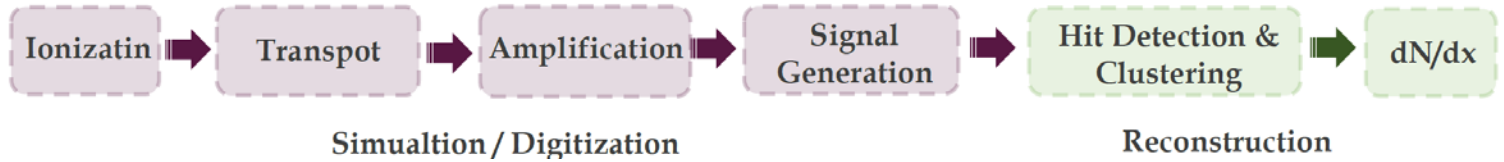


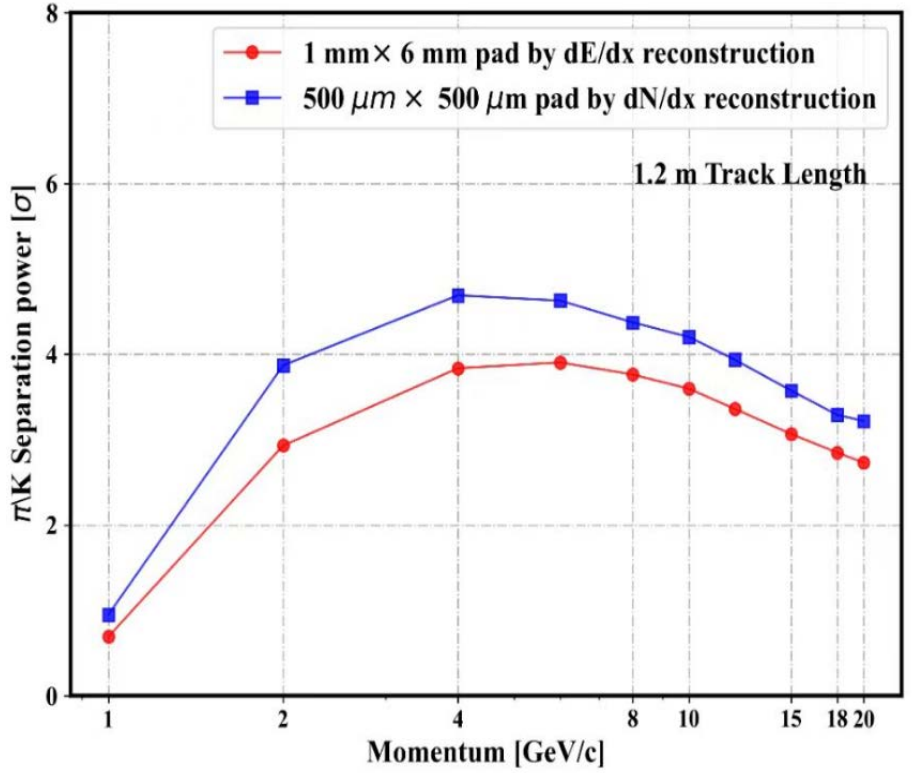
Easy-to-install modular design of TPC in CEPC ref-TDR

Full Simulation of Pixelated readout TPC

- Full simulation framework of pixelated TPC developed using Garfied++ and Geant4 at IHEP
- Investigating the π/κ separation power using reconstructed clusters, **a 3σ separation at 20GeV** with 120cm drift length can be achieved
- dN/dx significantly **improved PID resolution**





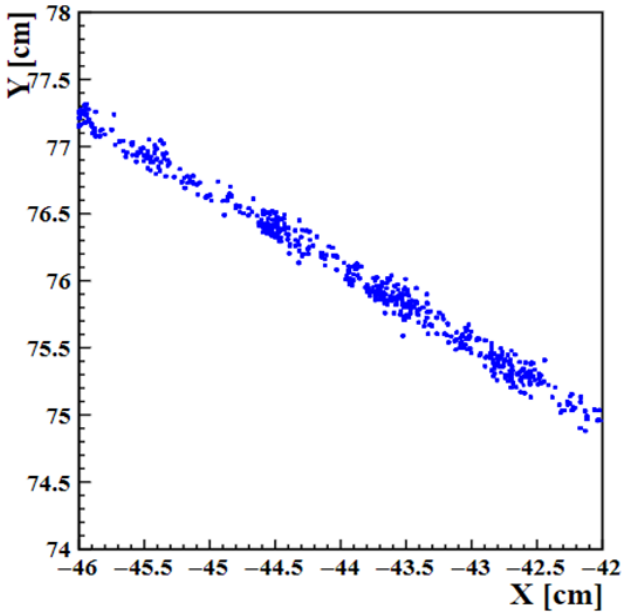


Simulation of TPC detector under 3T/2T and T2K mixture gas

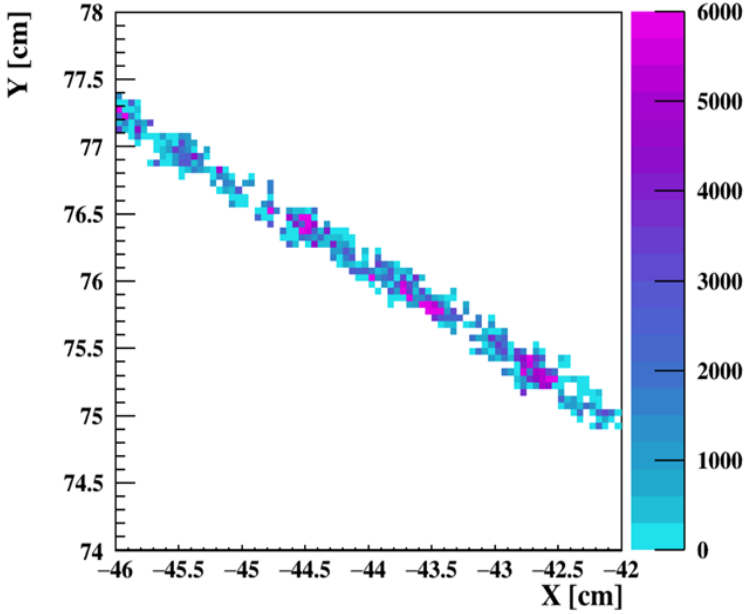
Cite#11: DOI: 10.22323/1.449.0553
Cite#12: EPS-HEP 2023 talk by Yue Chang

Optimization of the readout size

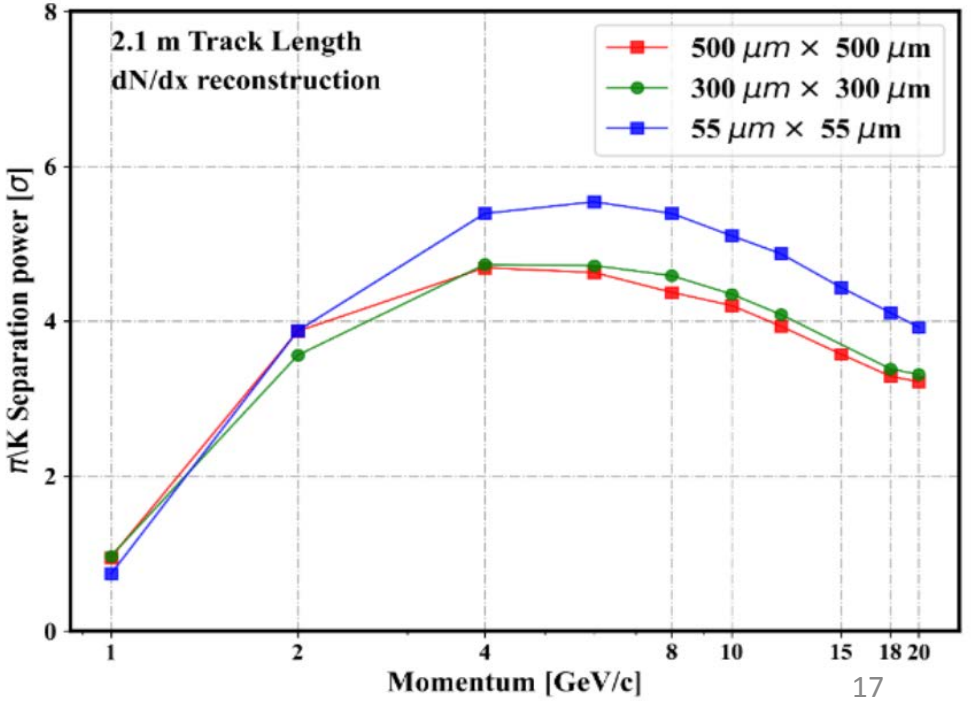
- Timepix (55μm×55μm) readout TPC prototype has been validation four times on DESY beams.
  - Power consumption: 2W/cm^2 ; Low power mode: 1W/cm^2 (**Too high power for pixelated readout**)
- Simulation results showed that readout size can be optimized at 300μm-500μm.
  - Reasonable readout channels and power consumption need to be studied
  - Focused on **100mW/cm^2 and 500μm readout** for CEPC refTDR (2-phase CO_2 cooling **OK!**)



pixel response (55 μm× 55 μm)



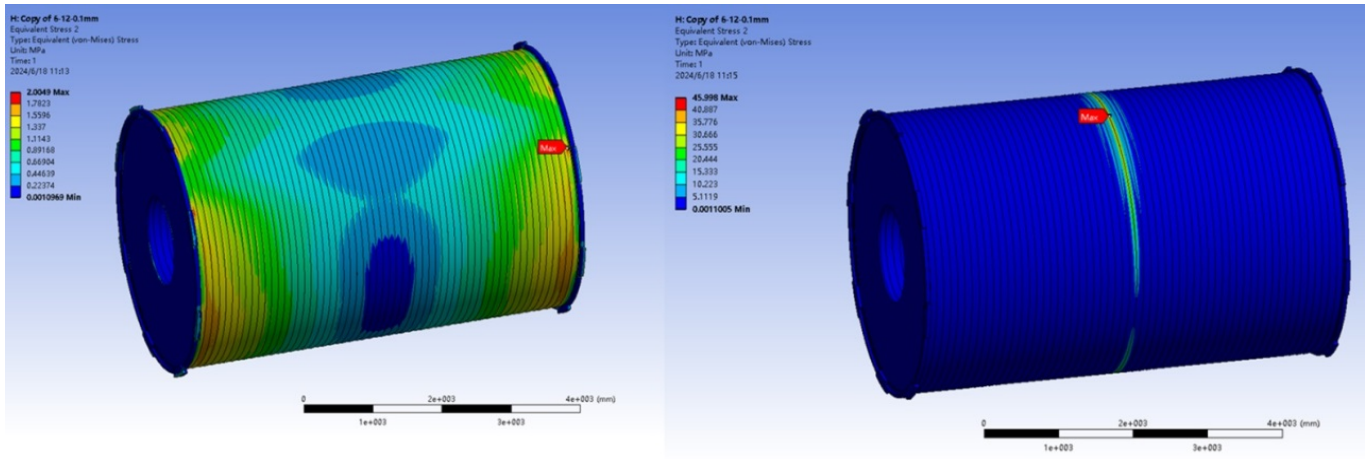
pixel response (500 μm× 500 μm)

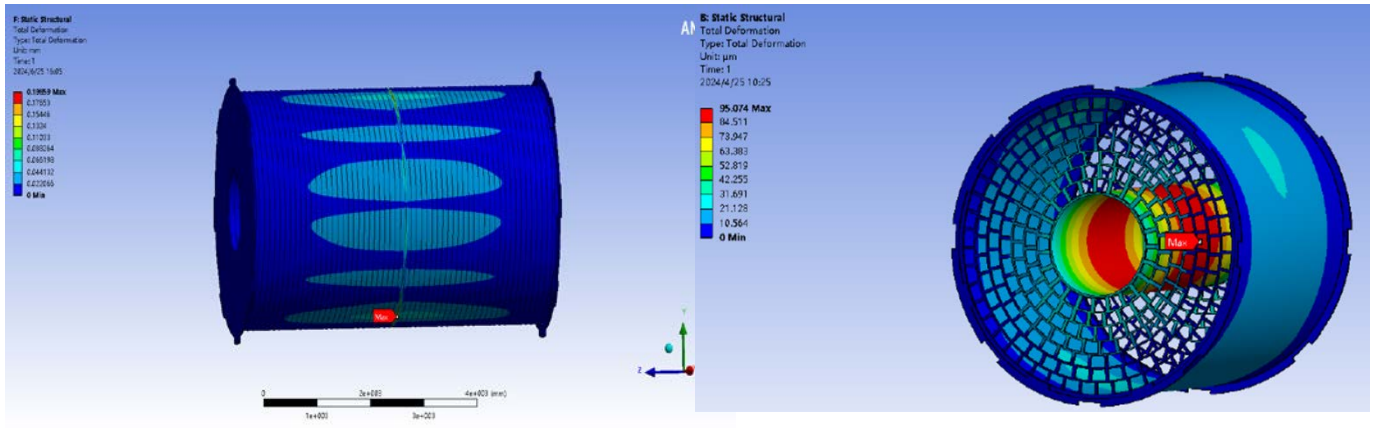


DOI: 10.1088/1748-0221/15/02/T02001
DOI: 10.1088/1748-0221/15/05/P05005

Ultra-light barrel and FEA analysis

- Consideration of new Carbon Fiber barrel instead of the honeycomb barrel (**~2% X_0**)
- **Ultra-light material** of the TPC barrel (QM55 CF) : **0.59% X_0 in total, including**
  - FEA preliminary calculation: 0.2mm carbon fibber barrel can tolerant of LGAD OTK (**100Kg**)
- Optimization of the connection back frame of the endcap (on going)





Material budget of TPC barrel

Layer of the barrels	D[cm]	X_0[cm]	d/X_0[%]
Copper shielding	0.001	1.45	0.07
CF outer barrel	0.020	25.28	0.08
Mirror strips	0.003	1.35	0.19
Polyimide substrate	0.005	32.65	0.02
Field strips	0.003	1.35	0.19
CF inner barrel	0.010	25.28	0.04
Sum of the material budget			**0.59**

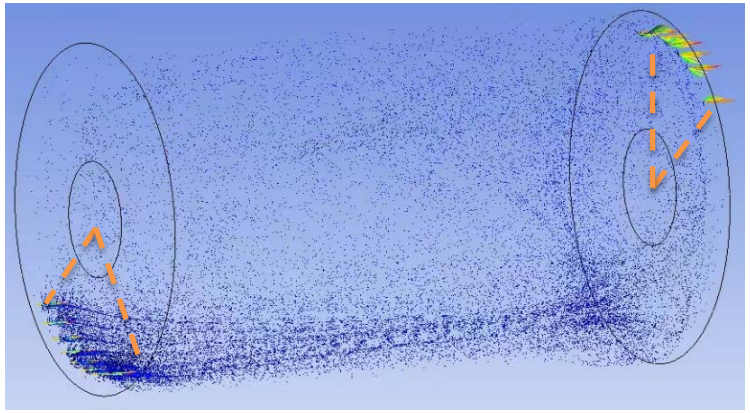
- **Low material of the TPC endcap**

15%X_0 in total, including

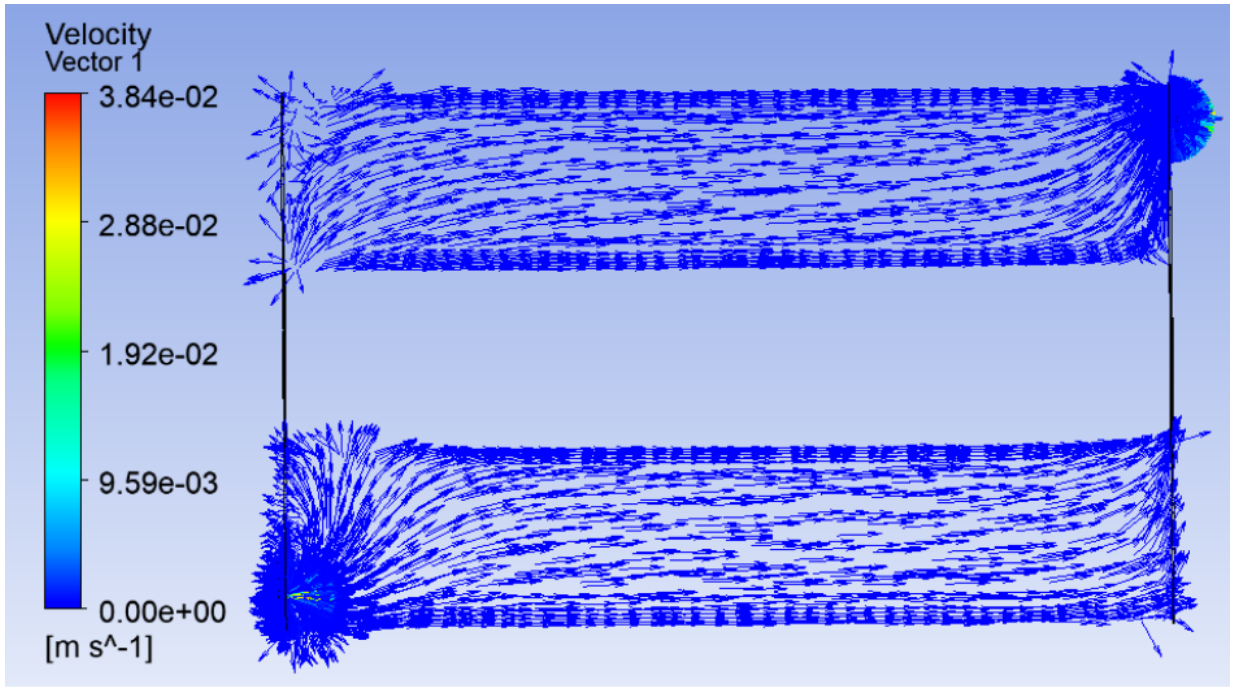
Readout plane, front-end-electronics	4%
Cooling	2%
Power cables	9%

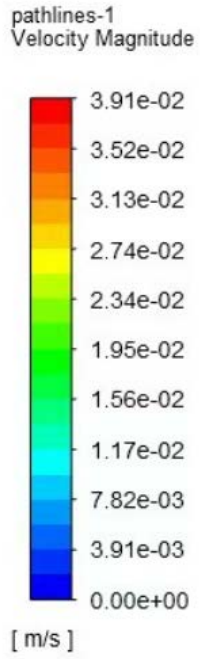
Optimization of Gas flow in Chamber

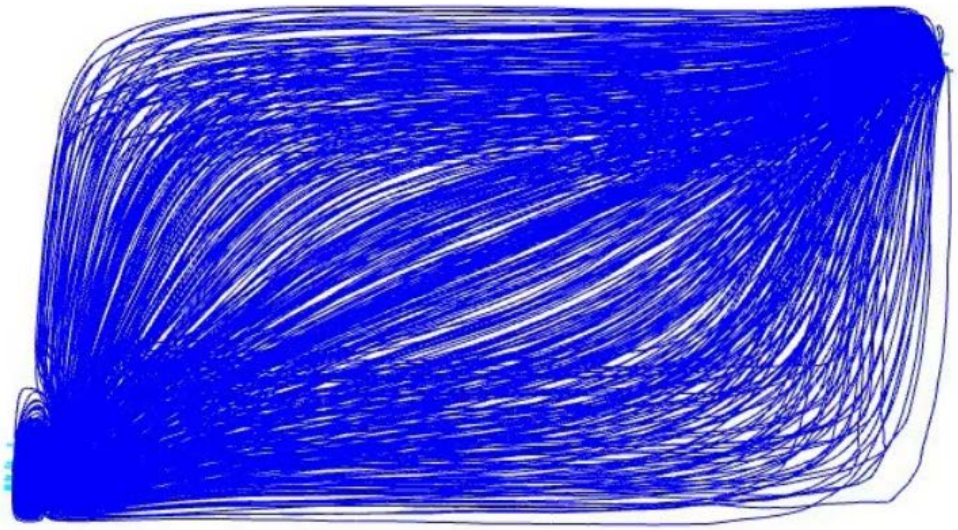
- Optimized design gas uniformity of **99% or more** in large TPC chamber
  - **8 Ø10mm** gas inlets + **8 Ø10mm** gas outlets (opposite, 90°/endcap)
  - Working gas flow: 300 – 500 mL/min
  - **Online monitoring system**: O_2 (ppm) and water H_2O (ppm)
  - Friendly the gases recycle system and mesh cathode considered



Optimized inlet and outlet in Chamber



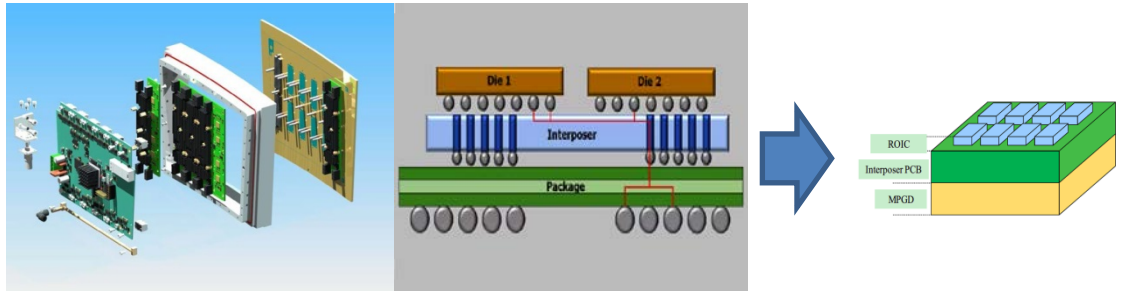


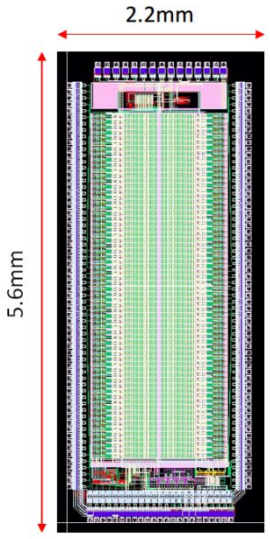


Simulation of gas flow and uniformity distribution in TPC Chamber

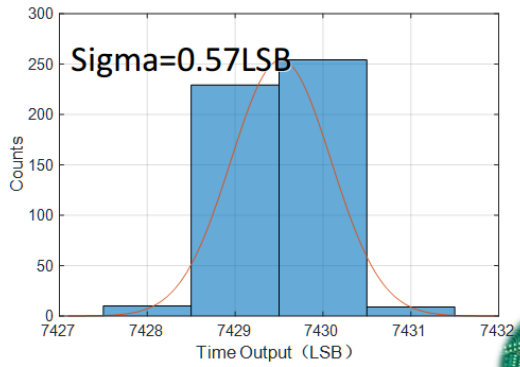
Detailed design of electronics and BEC

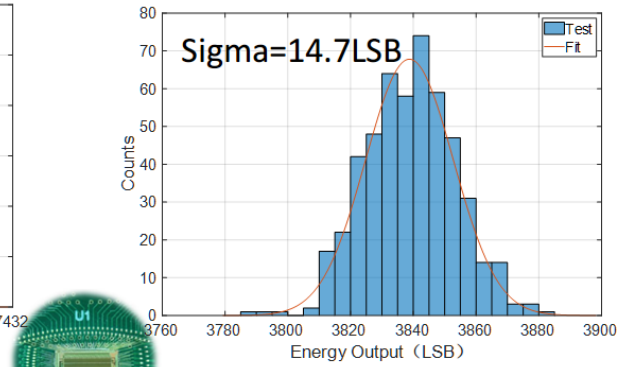
- Pixel Readout Electronics: TEPix development
  - Multi-ROIC chips + Interposer PCB as RDL
  - Four-side bootable
- TEPix: Low power Energy/Timing measurement
  - LPower Consumption ~ 0.5mW/ch
  - Timing ~ <1LSB(10ns)
  - Noise ~ < 300e (even high gain)

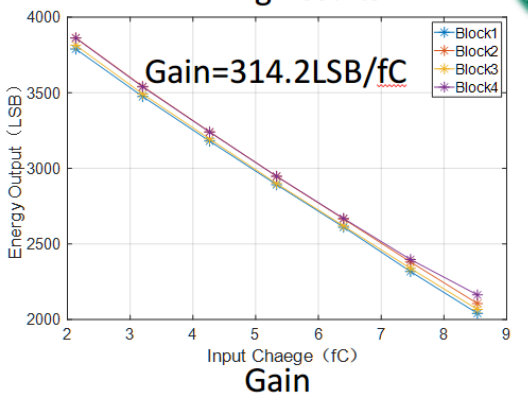


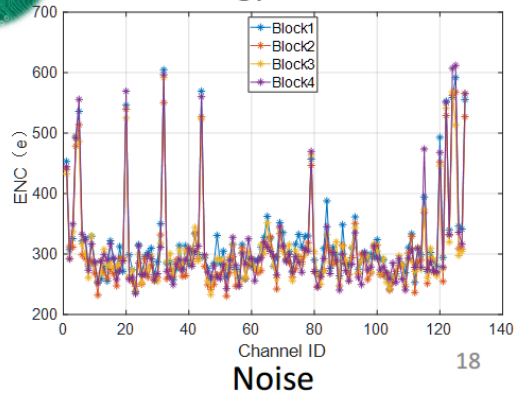


Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns





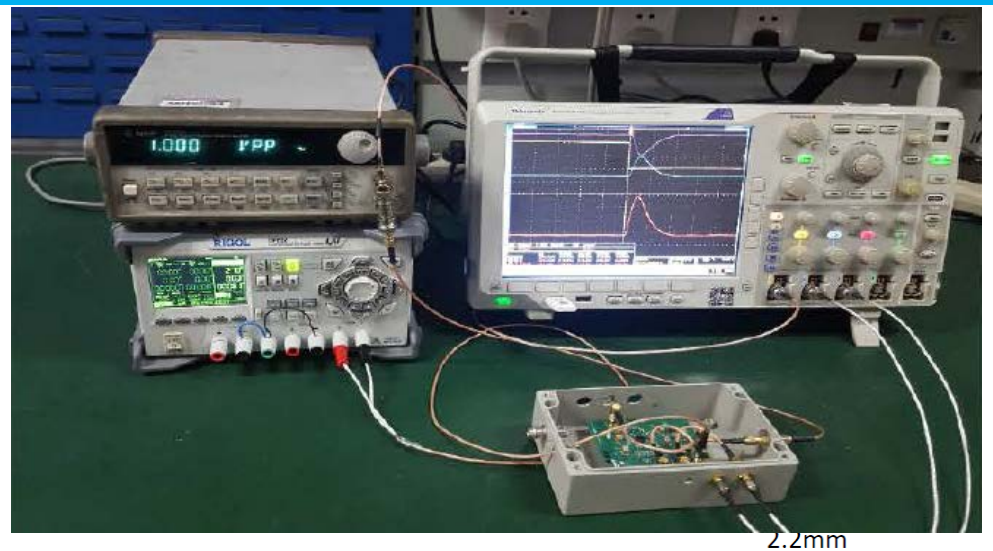


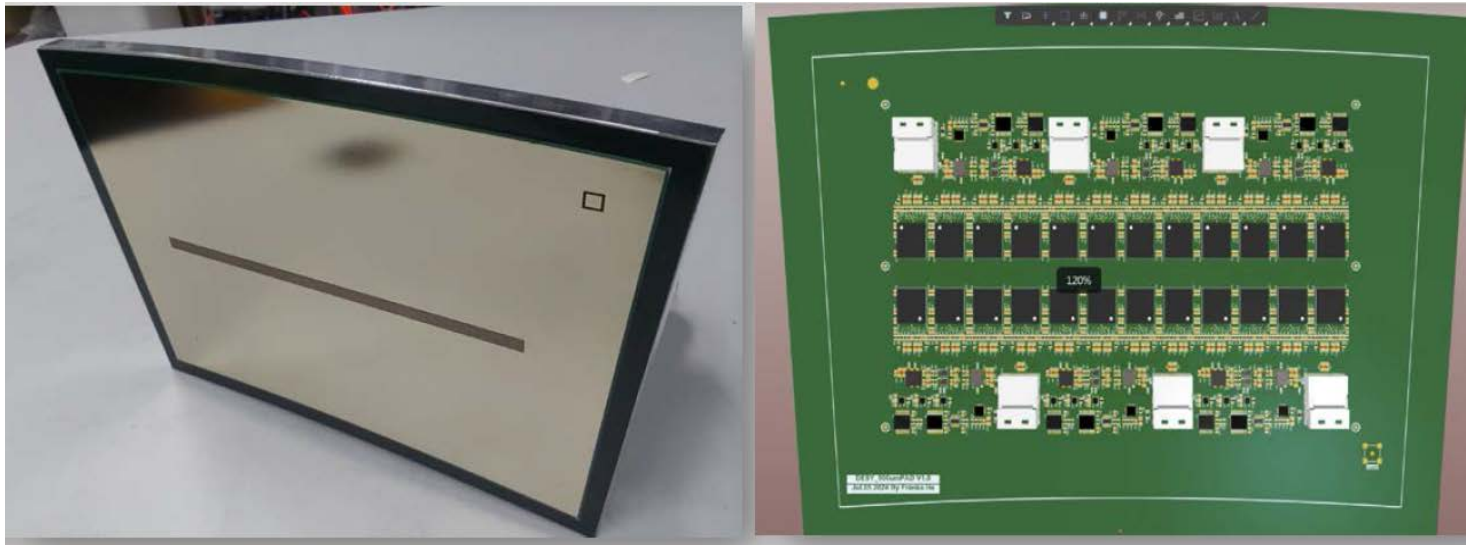


FEE ASIC: TEPIX—Test Results in May

Validation and commission of TPC prototype

- **R&D on Pixelated TPC readout for CEPC TDR**
  - Pixelated readout TPC ASIC chip developed and **2nd prototype wafer has done** and tested.
  - The TOA and TOT can be selected as the initiation function in the ASIC chip
- **Prototyping pixelated readout TPC detector**
  - The validation of the prototype assembled for beam test





Photos TPC modules assembled for the beam test

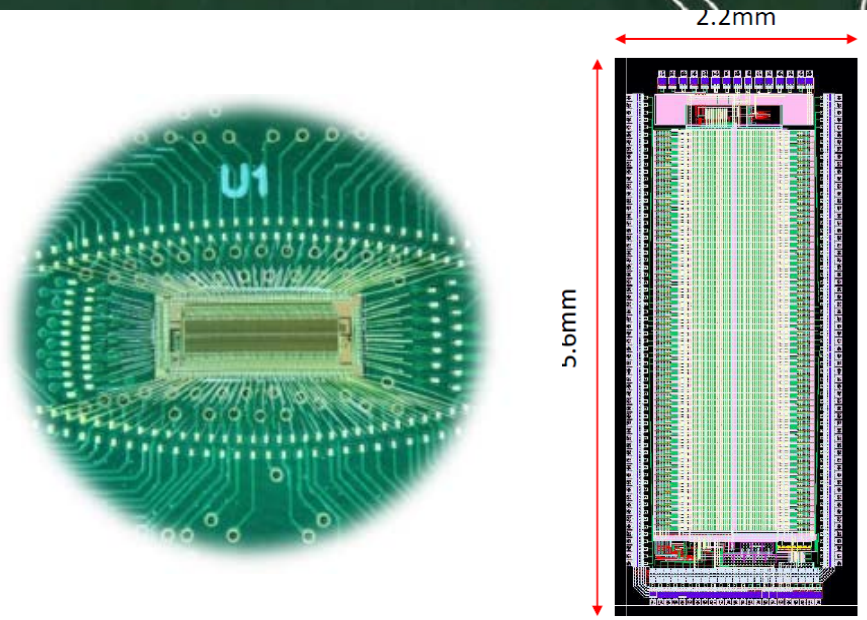
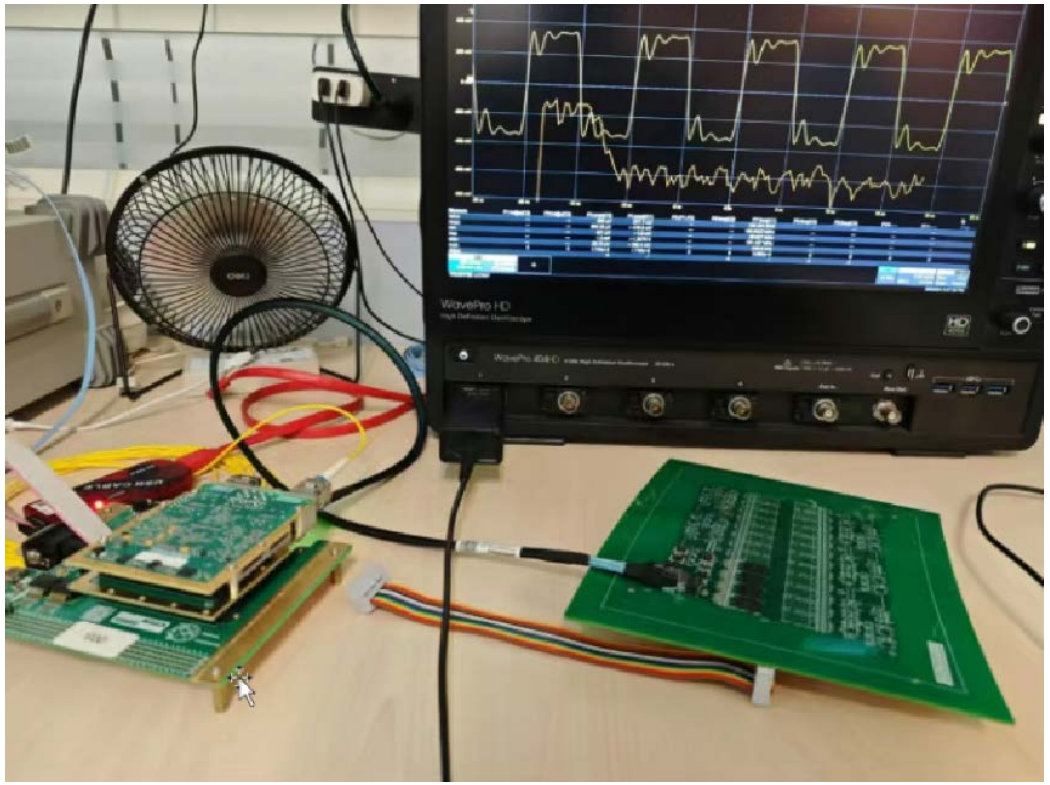
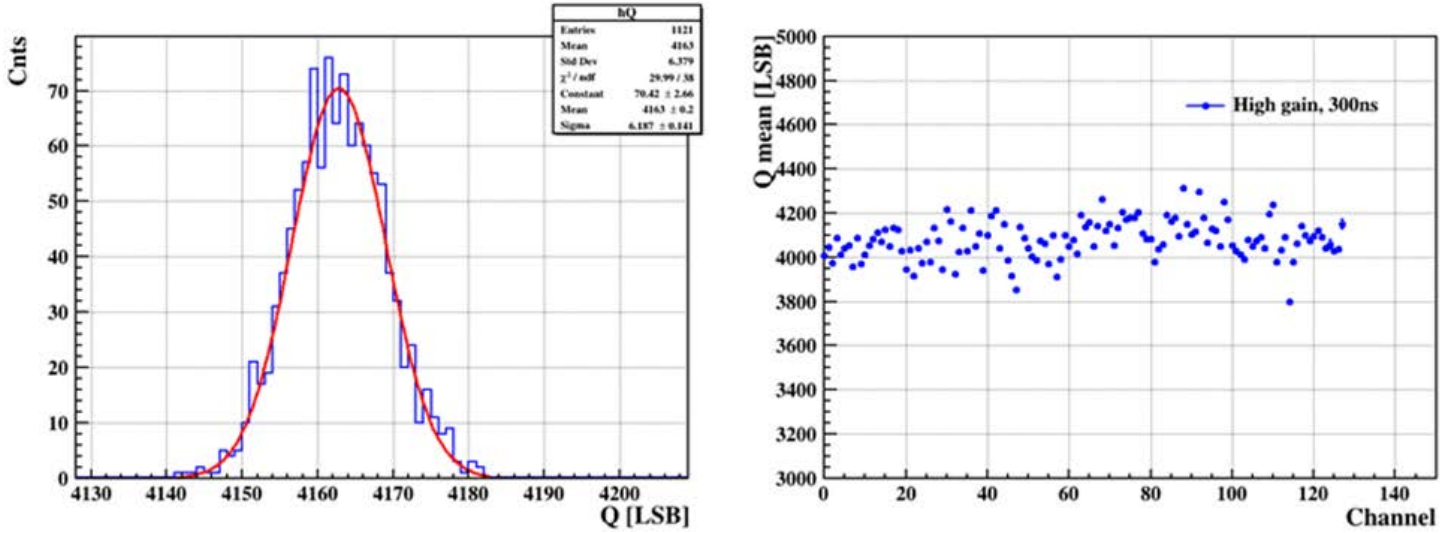


Photo and layout of ASIC Chip R&D for TPC

Progress of TPC prototype

- Completed testing of TEPIX, a pixel-based readout chip to **determine that the chip is operational**.
  - Inputted square wave signals, external trigger mode
  - Chip outputs data functional and the data taking per channel.



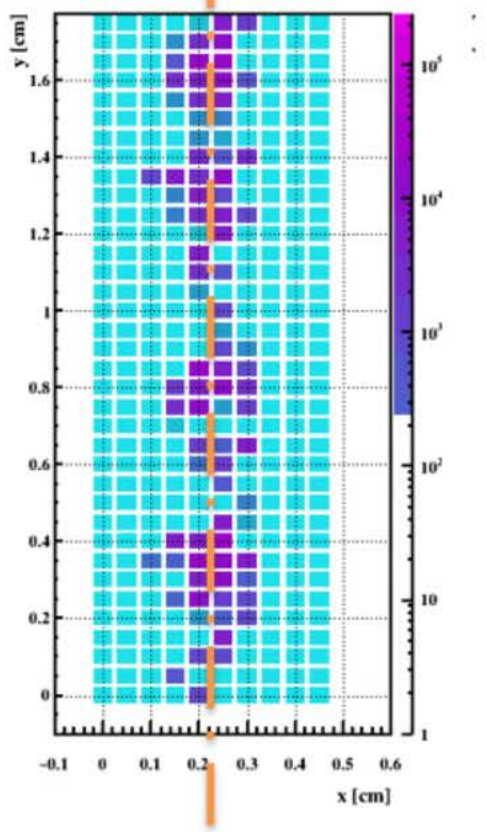


Amplitude distribution per channel(left) and Uniformity per channel (right)

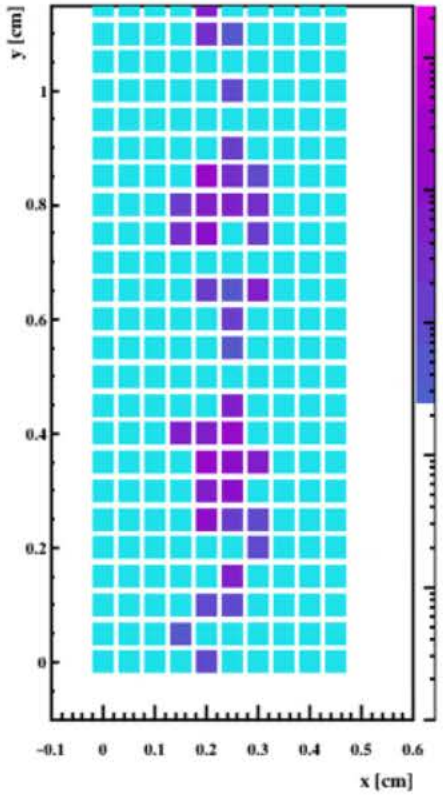
Development of the data analysis: Cluster Finding

- The preliminary simulation data analysis are under development including the drift, diffusion and avalanche of the detector. (On-going)

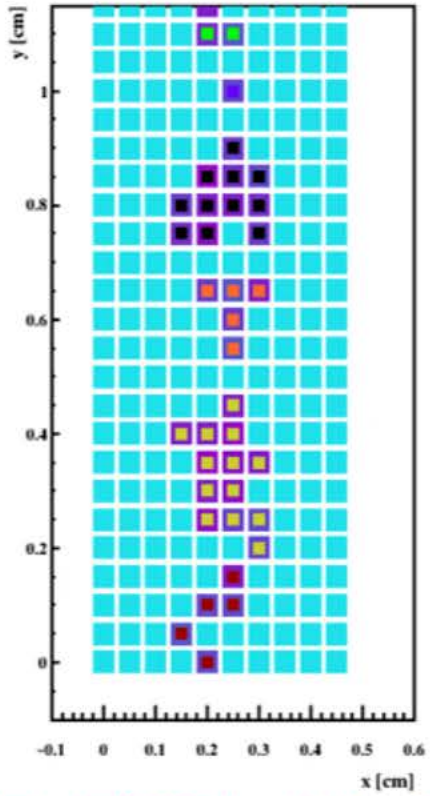
1、不加noise cut前pixel响应



2、加noise cut后pixel响应，active pixels降低



3、简单聚类过程实现，ClusterFinder



一个pixel，周围一圈有响应，合并一个cluster

5.0 GeV e- @ B=1T, 20cm drift length

Working plan

- Short term working plan (**before June 2025**)
  - Optimization of TPC detector for CEPC ref-TDR
  - Prototyping R&D and validation using FEE
    - mechanics, manufacturing, beam testing, full drift length prototype
  - Performance of the simulation and optimize deep learning algorithm

- Long term working plan (**about three years**)
  - Development of the pixelated TPC prototype with low power consumption FEE ASIC
    - Beam test collaborated with LCTPC collaboration
  - Development of the full drift length prototype
    - Drift velocity. Attachment coefficient, T/L Diffusion along the drift length

Summary

- TPC detector prototype R&D using the pad readout towards the pixelated readout for the future e^+e^- colliders, espial to the high luminosity Z pole run at future e^+e^- collider. DC will be as the alternative detector at Tera-Z.

- Pixelated TPC is choose as the baseline detector as main track in CEPC ref-TDR. The simulation framework has been developed using Garfied++ and Geant4 at IHEP. Some validation of TPC prototype have been studies.

- Synergies with CEPC/FCCee/EIC/LCTPC allow us to continue R&D and ongoing, we learn from all of their experiences. **All will input to CEPC ref-TDR in next some months.**

CEPC WS 2024

The 2024 International Workshop on the High Energy Circular Electron Positron Collider

Oct 22 – 27, 2024
Hangzhou Platinum Hanjue Hotel
Asia/Shanghai timezone

https://indico.ihep.ac.cn/event/22089

Thank you for your attention!

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