CEPC Gaseous Track Detector

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On behalf the gaseous track detector group

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Content

- Motivation and physics requirements
- Technology survey and our choices
- Technical challenges and R&D efforts
- Detailed design including electronics, cooling and mechanics
- Performance from simulation
- Research team and working plan
- Summary

Motivation

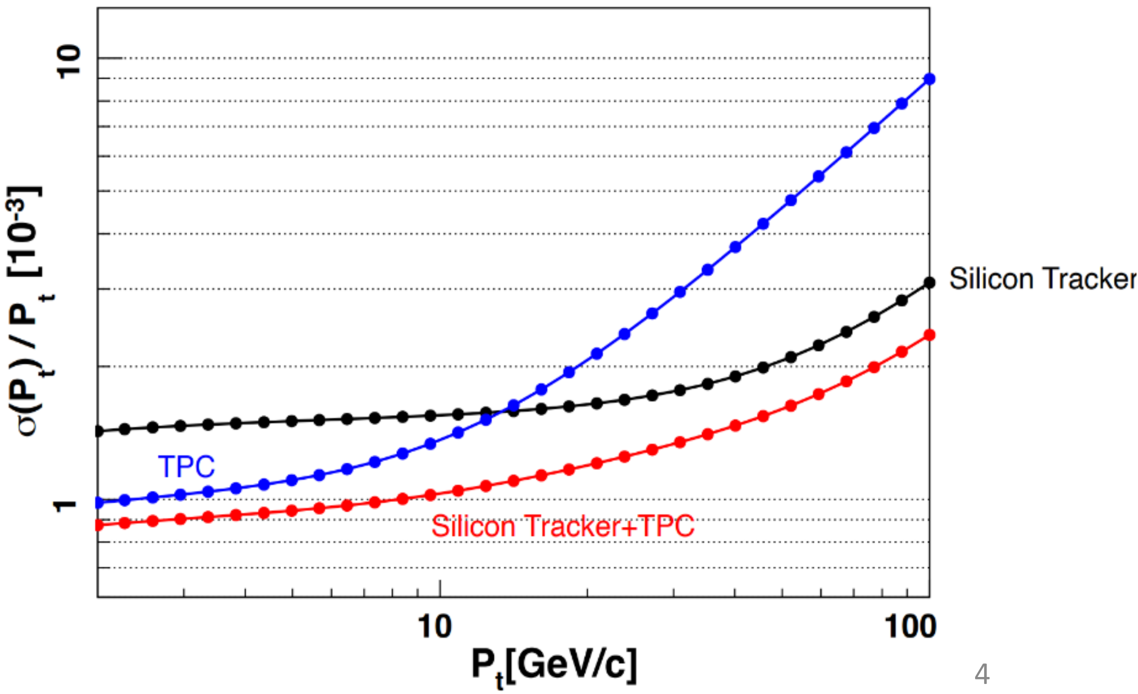
- This talk relates to the CEPC Physics and Detector Ref-TDR.
  - Chapter 5: Gaseous tracker
  - Draft of content listed →

Chapter 5 Gaseous trackers

Physics requirement

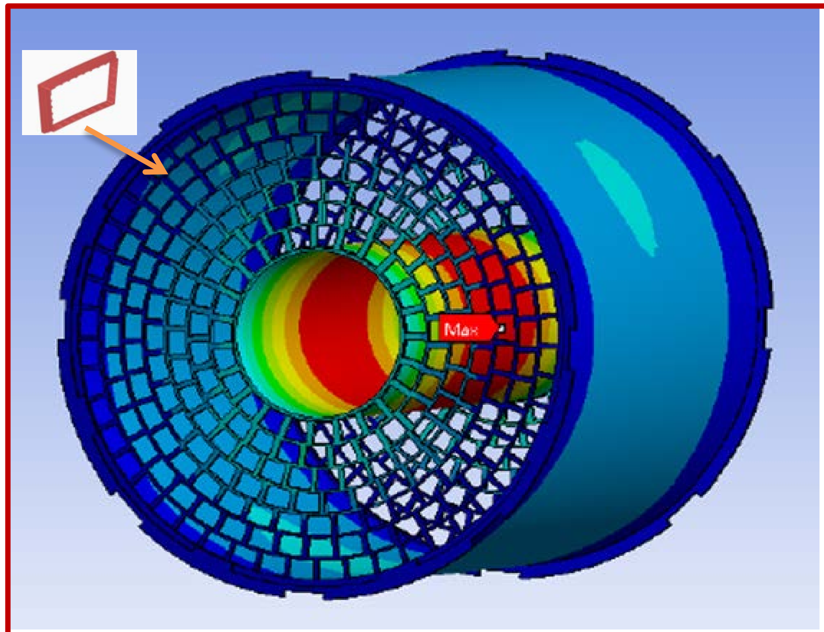
- CEPC operation stages in TDR: **10-years Higgs → 2-years Z pole → 1-year W**
- Phys. Requirements of the track detector
  - Thousands of hits with high spatial resolution compatible with PFA algorithm (low X_0)
- Beneficial for jet & differential at higher energy
  - Highly requirements for excellent 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	$\sigma_{r\phi} \sim 3\ \mu\text{m}$, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2\times10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\text{GeV}^{-1})$
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 4D crystal calorimeter	EM energy resolution $\sim 3\%/\sqrt{E(\text{GeV})}$ Granularity $\sim 2\times2\times2\ \text{cm}^3$
Magnet system	Ultra-thin High temperature Superconducting magnet	Magnet field $2-3$ T Material budget $< 1.5X_0$ Thickness < 150 mm
Hadron calorimeter	Scintillating glass Hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(\text{GeV})}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(\text{GeV})}$

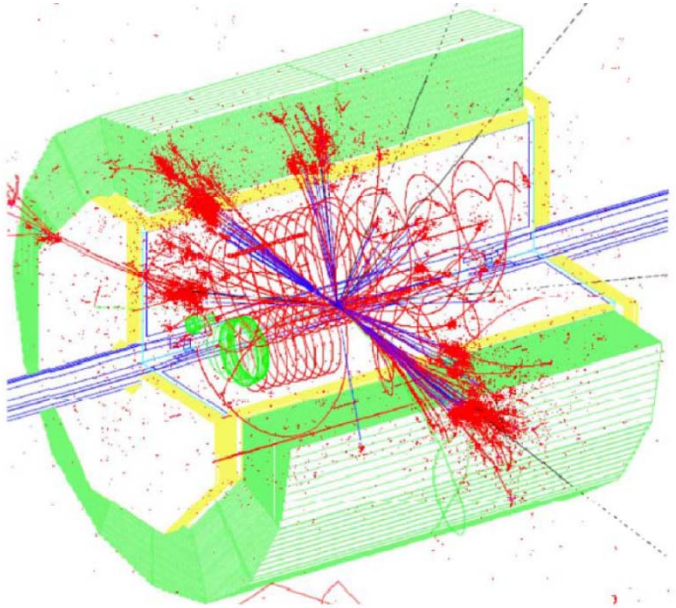


Technology survey and our choices

- 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

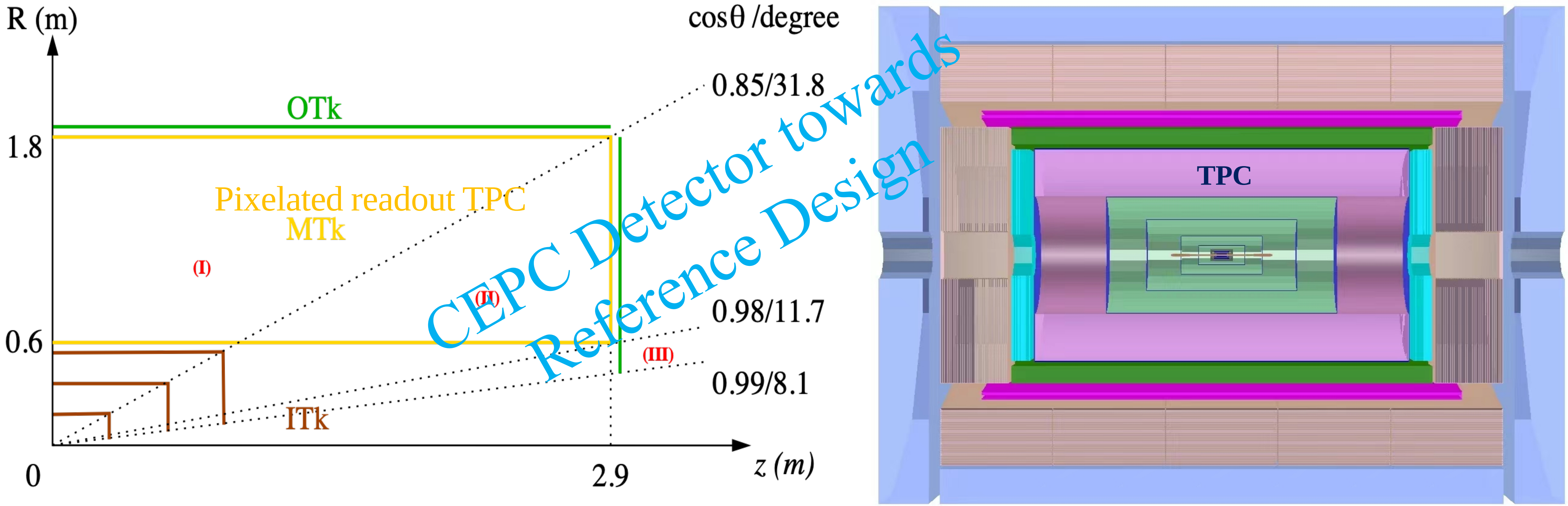


Time Projection Chamber

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.



Geometry of the track detector system in CEPC TDR

Technical challenges and R&D efforts

Main Technical Challenges

- **Pixelated readout TPC (Baseline)**

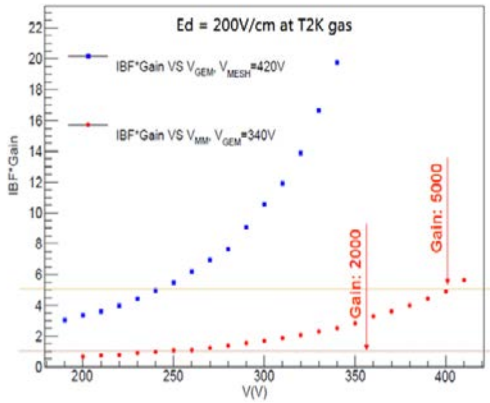
Critical key issues:

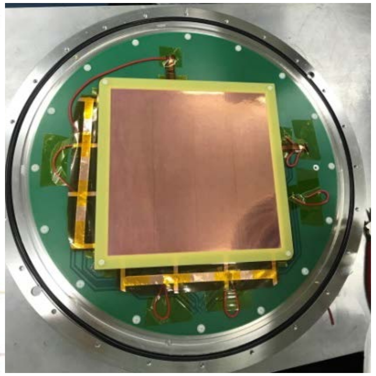
  - **Material budget at endcape/barrel √**
  - **Occupancy and hit density at Tera-Z √**
  - **Ion backflow suppression √**
  - **Running at 2 Tesla √**
  - **Improved PID √**
  - **Reasonable channels(ongoing)**
  - **Reasonable power consumption (ongoing)**

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

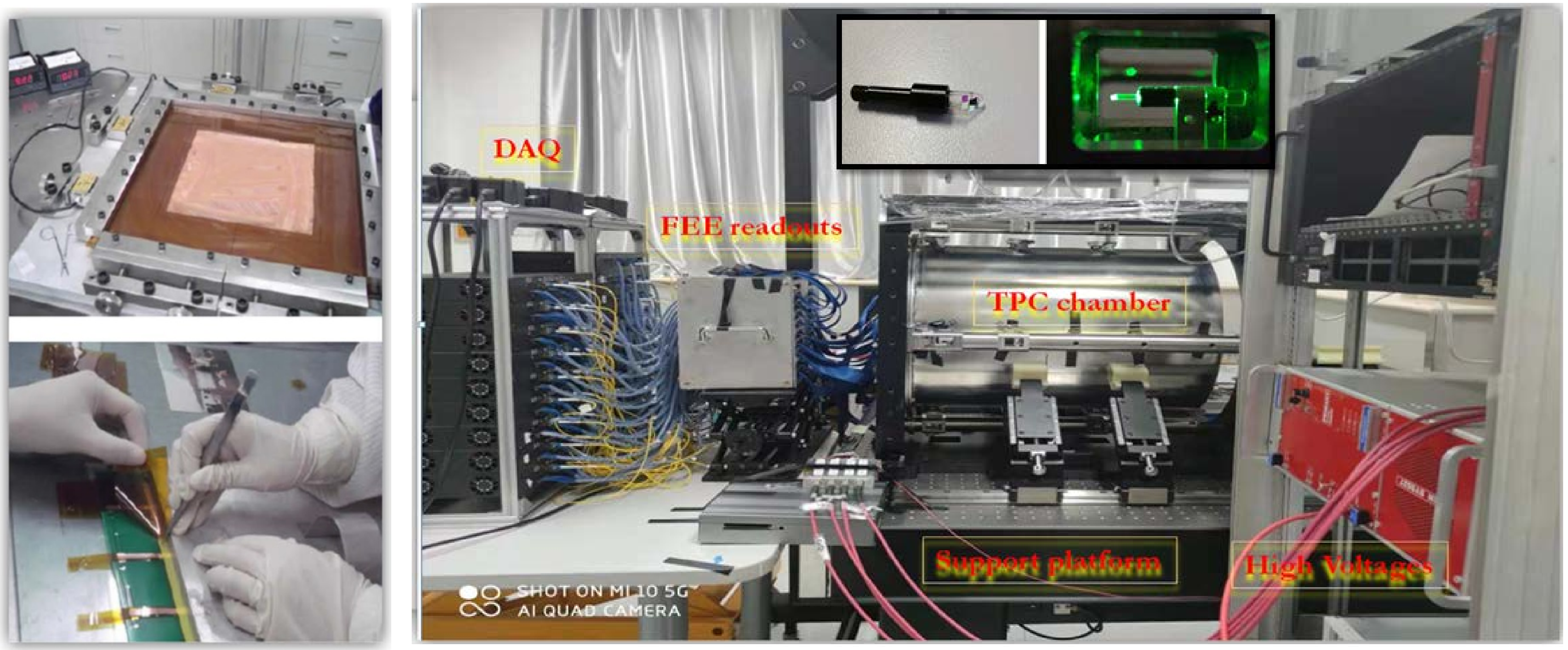
TPC prototype R&D efforts and results

- **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 **$\sigma_{r\varphi} \leq 100\ \mu m$ and dE/dx resolution of 3.6%**
  - FEE chip: reach ~**3.0mW/ch with ADC** and the pixelated readout R&D

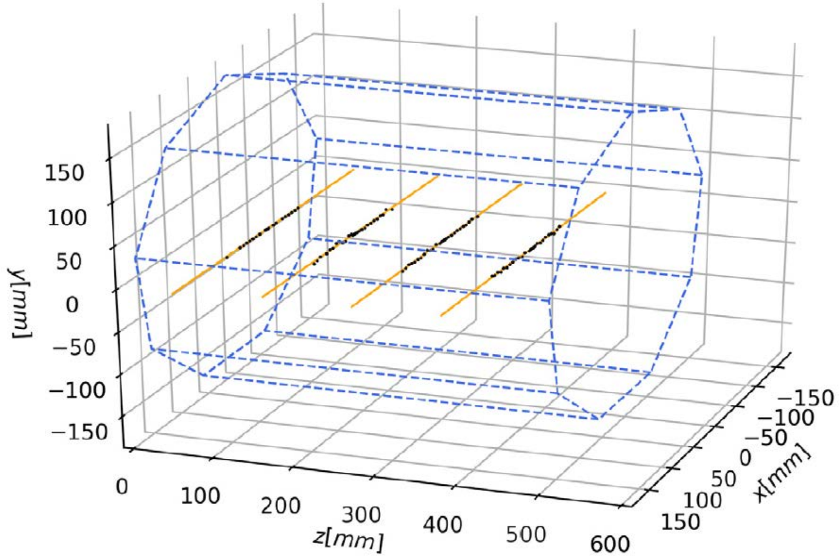




Ion suppression TPC module R&D



TPC prototype with integrated 266nm UV laser



Tracks reconstruction

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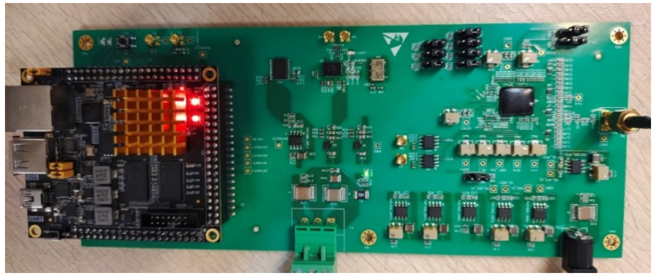
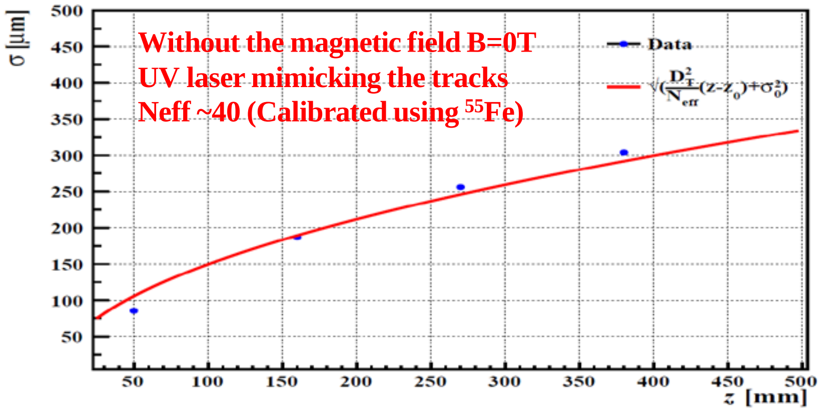
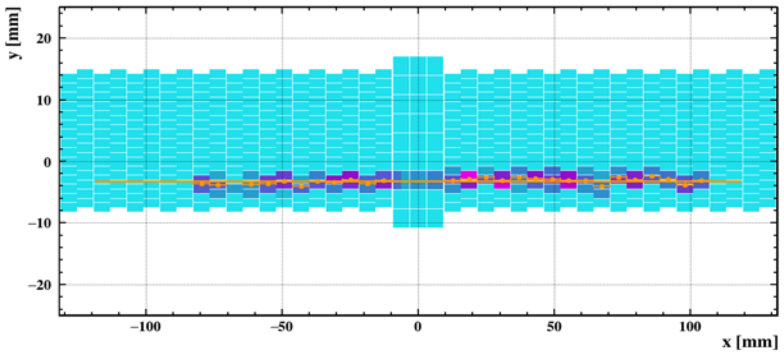
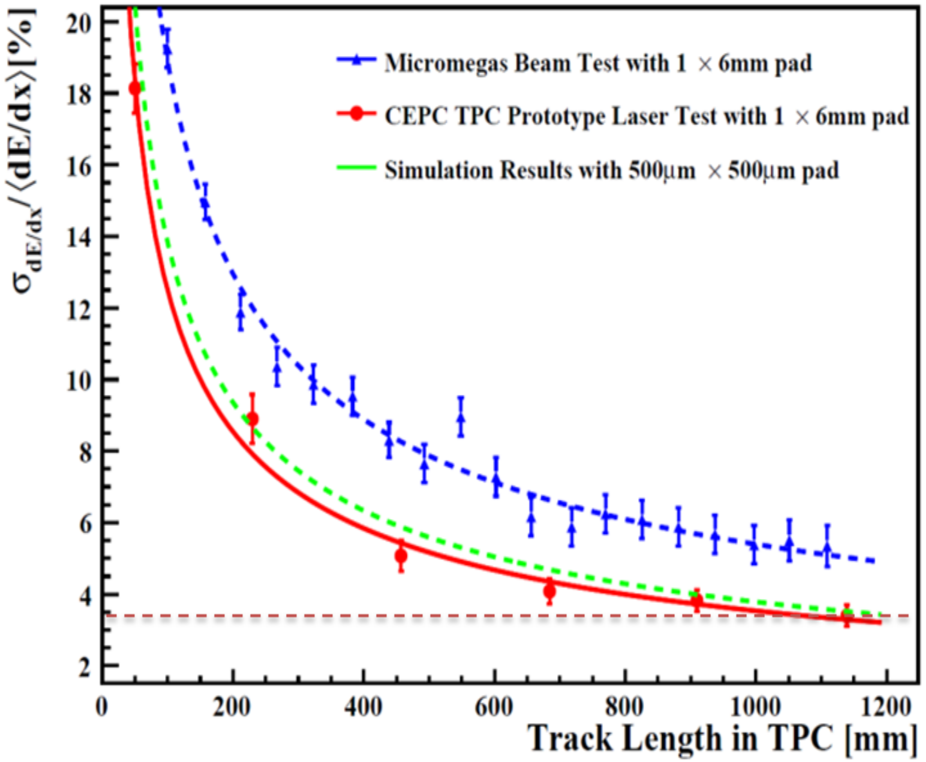
Highlights of TPC prototype R&D

- **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









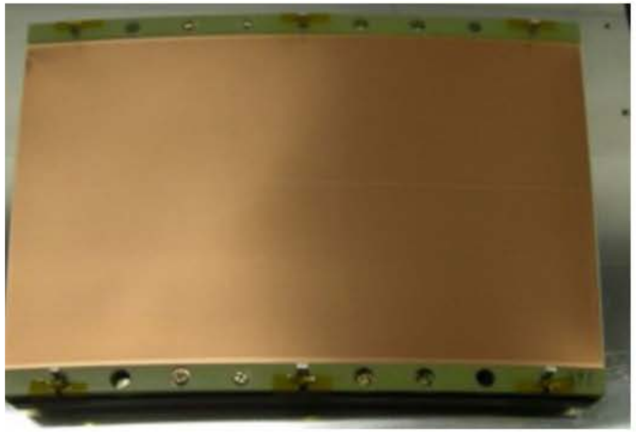
Publications by CEPC TPC group in 2018-2024:

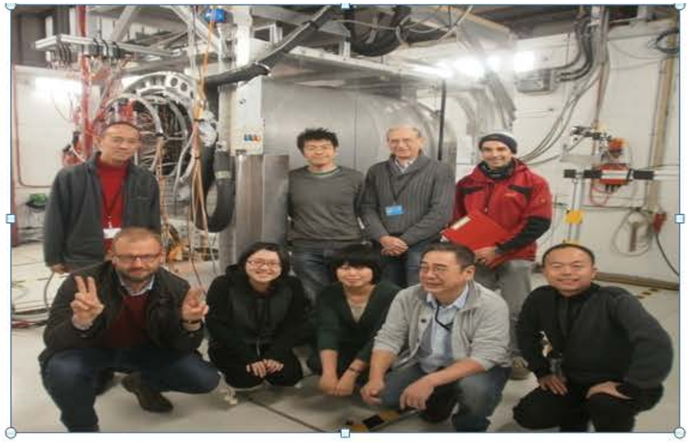
- https://doi.org/10.1088/1748-0221/18/08/E08002
- https://doi.org/10.22323/1.449.0553
- https://doi.org/10.1016/j.nima.2022.167241
- https://doi.org/10.1109/NSS/MIC44867.2021.9875566
- https://doi.org/10.1109/NSS/MIC44845.2022.10399097
- https://doi.org/10.1088/1748-0221/15/09/C09065
- https://doi.org/10.1088/1748-0221/15/05/P05005
- 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

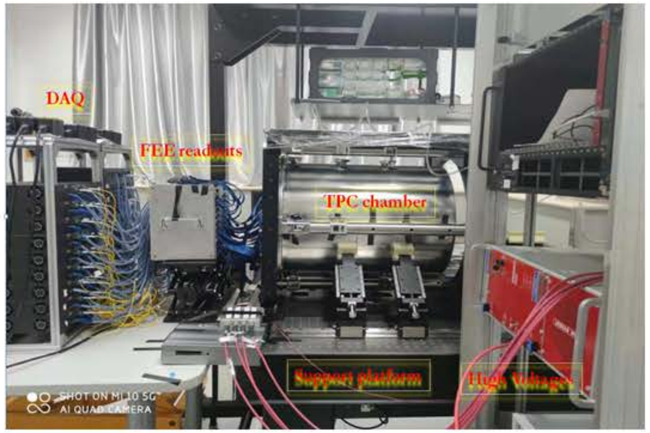
Activity international collaboration

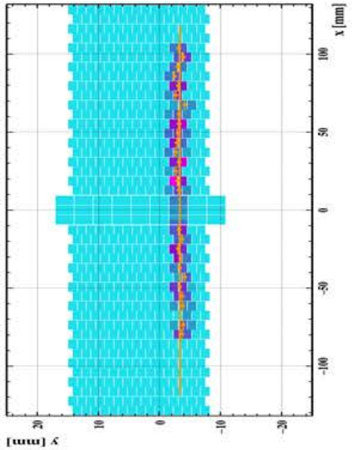
- **Activity collaboration:** Pixelated readout and Pad readout from IHEP and LCTPC collaboration
  - Large Prototype setup have been built to compare different detector readouts for Tera-Z
  - PCMAG: B < 1.0T, bore Ø: 85cm, Spatial resolution of $\sigma_{r\phi} \leq 100$ μm
  - Collaboration implement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

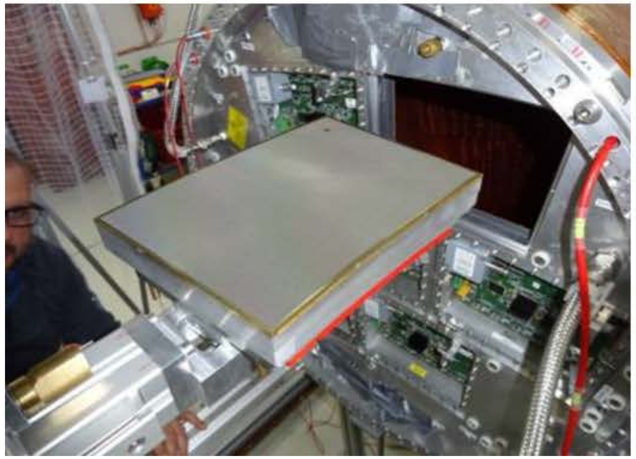
ArXiv. (2023)2006.08562
NIM A (2022) 167241
ArXiv (2022)2006.085
JINST 16 (2021) P10023
JINST 5 (2010) P10011
NIM A608 (2009) 390-396

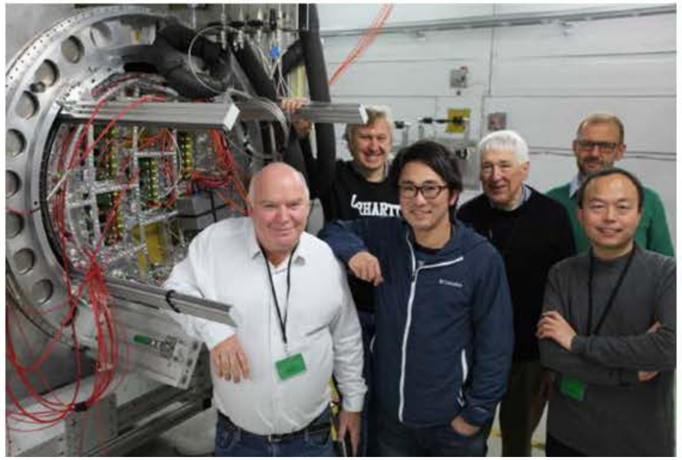


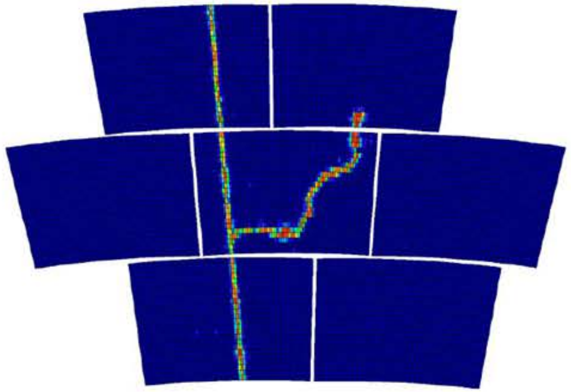








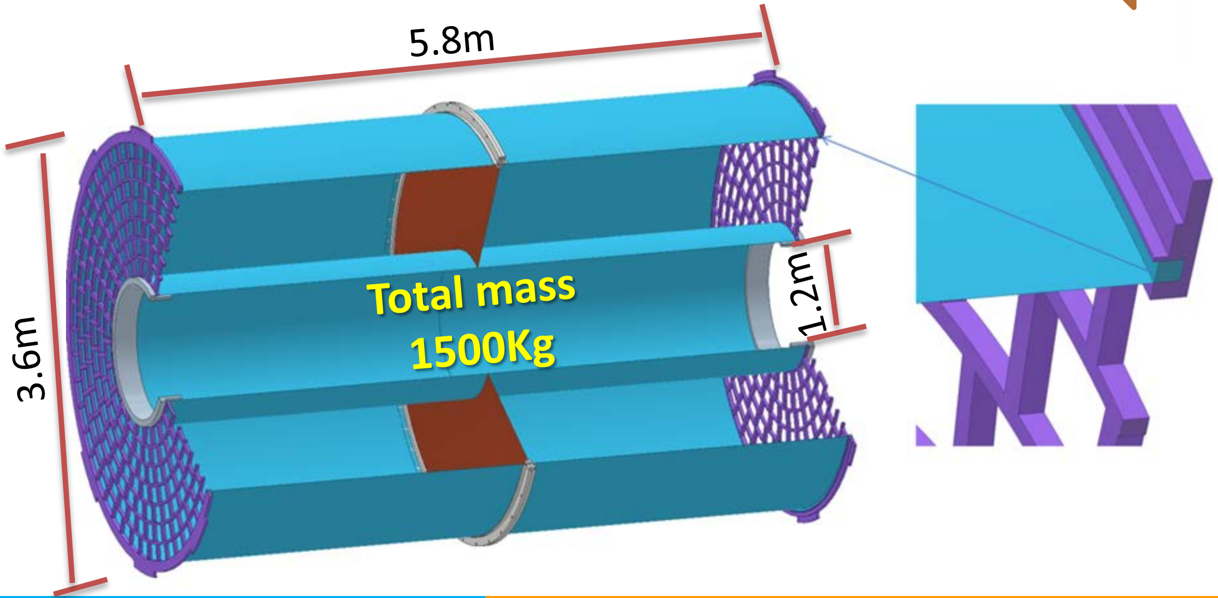




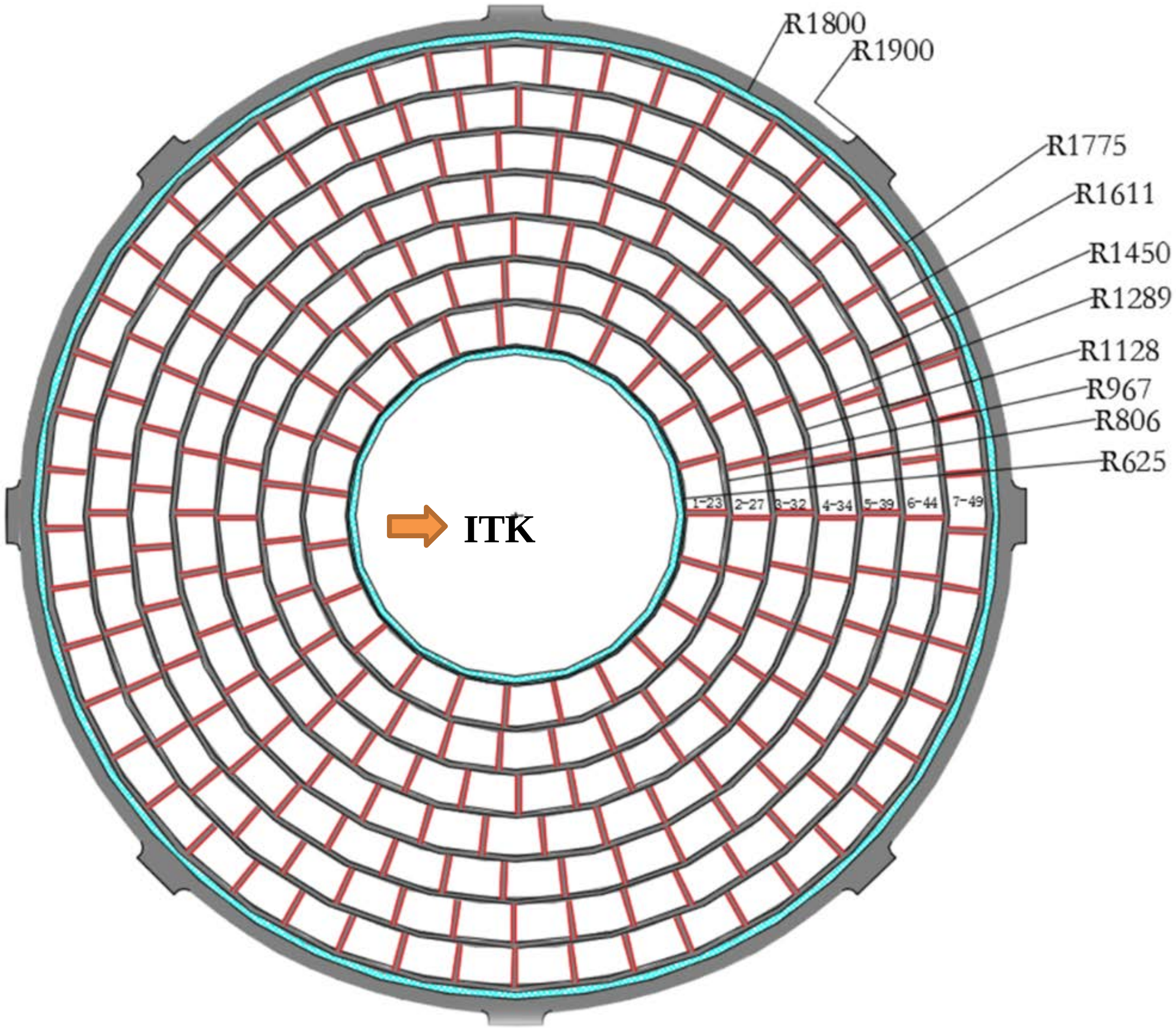
Detailed design and performance of Baseline: TPC

Detailed design of mechanics

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



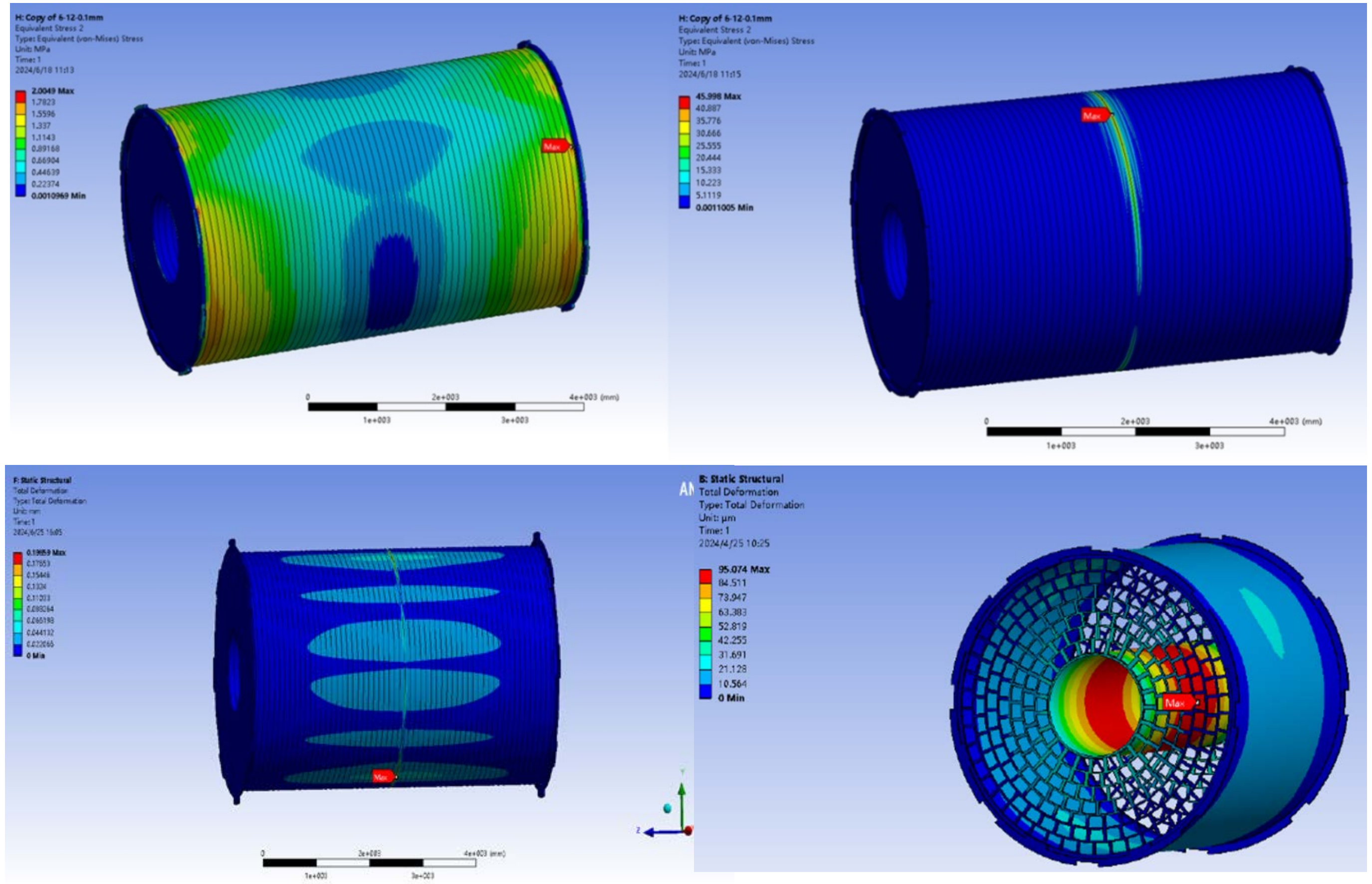
OTK ⇦ ⇨ ITK



Detailed design of TPC detector in ref-TDR

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 OTK (**~200Kg**)
- 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**

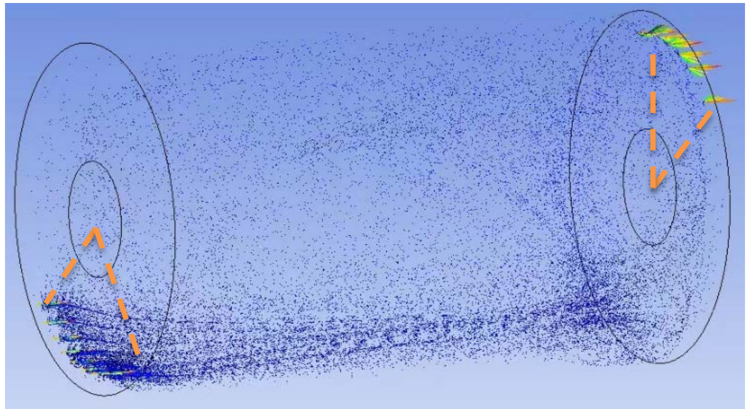
- **Low material of the TPC endcap**

15%X_0 in total, including

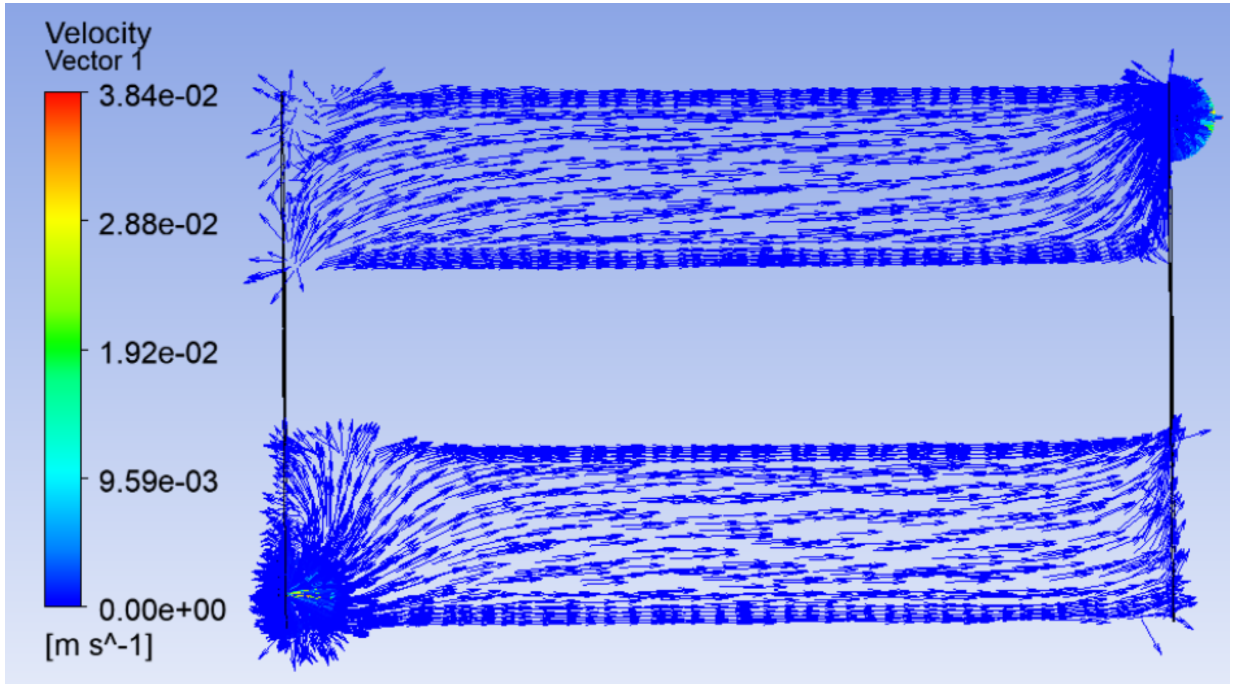
Readout plane, front-end-electronics	4%
Cooling	2%
Power cables	9%

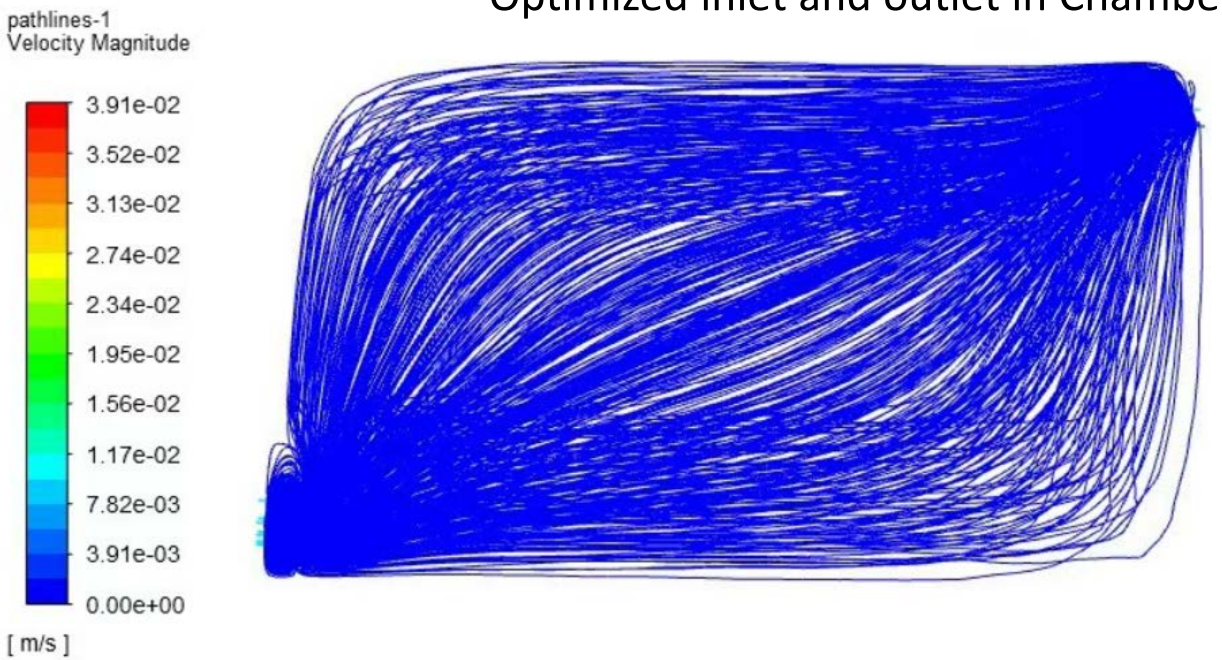
Optimization of Gas flow in Chamber

- 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: 0.3 – 0.5 L/min
  - **Online monitoring system**: O_2 (ppm) and water H_2O (ppm)
  - Friendly the gases recycle system also considered



Optimized inlet and outlet in Chamber





Simulation of gas flow and uniformity distribution in TPC Chamber

Full Simulation of Pixelated readout TPC

Simulation / Digitization Framework

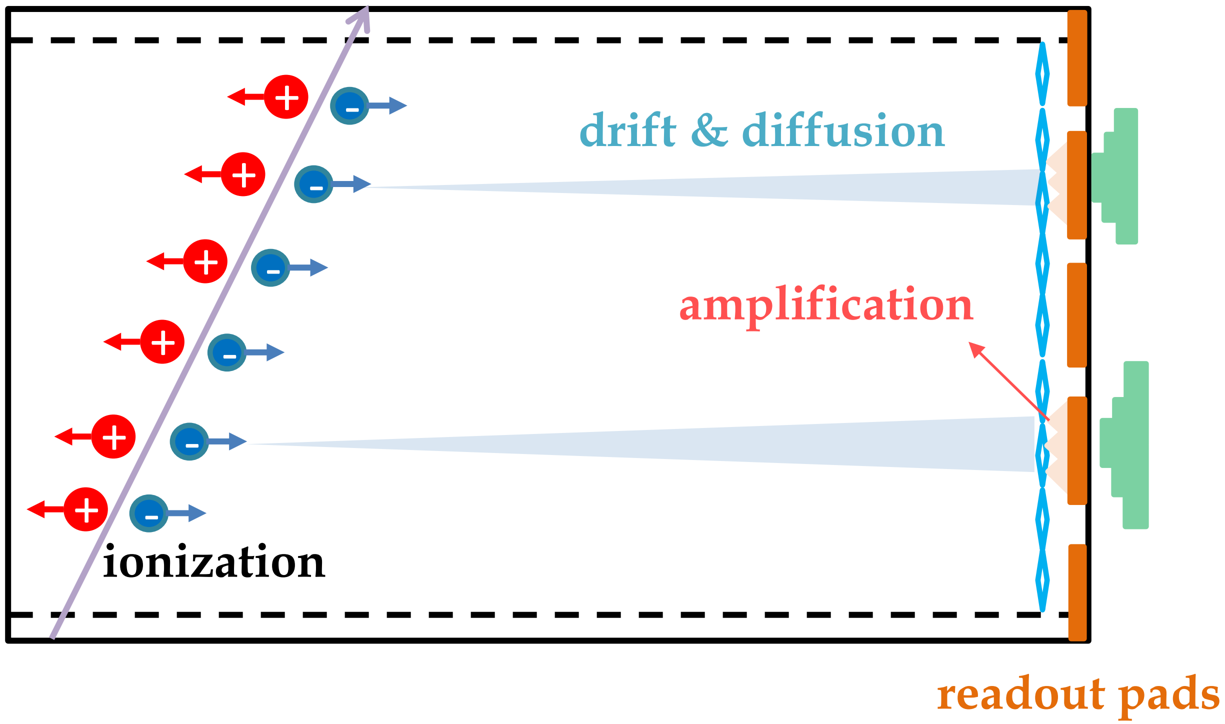
Ionization → Transport → Amplification → Signal Generation

Simulation:

- Full geometry TPC
- Ionization generation by Garfield++
- Drift and diffusion from parameterized model based on Garfield++ simulation

Digitization (Refer to the TPC module and prototype**):**

- Electronic noise: 100 e-
- Amplification:
  - Number of electrons: 2000
  - Signal size in space: 100 um



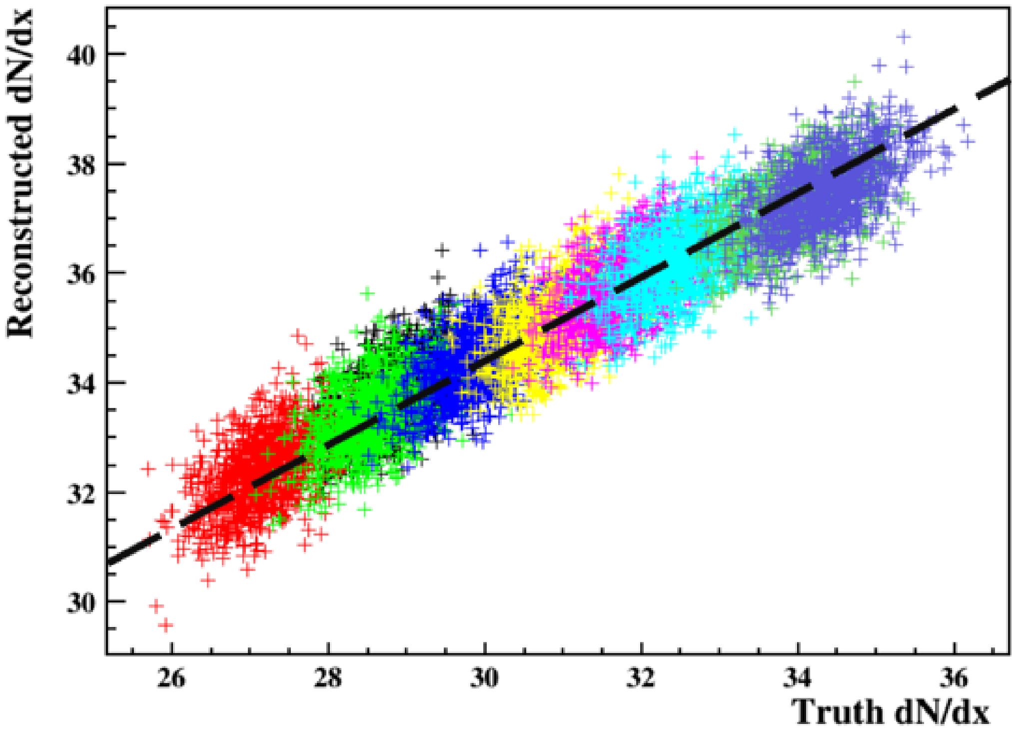
Simulation of TPC detector under 3T/2T and T2K mixture gas

DOI: 10.22323/1.449.0553
EPS-HEP 2023 talk by Yue Chang

Performance of Pixelated readout TPC

Reconstruction:

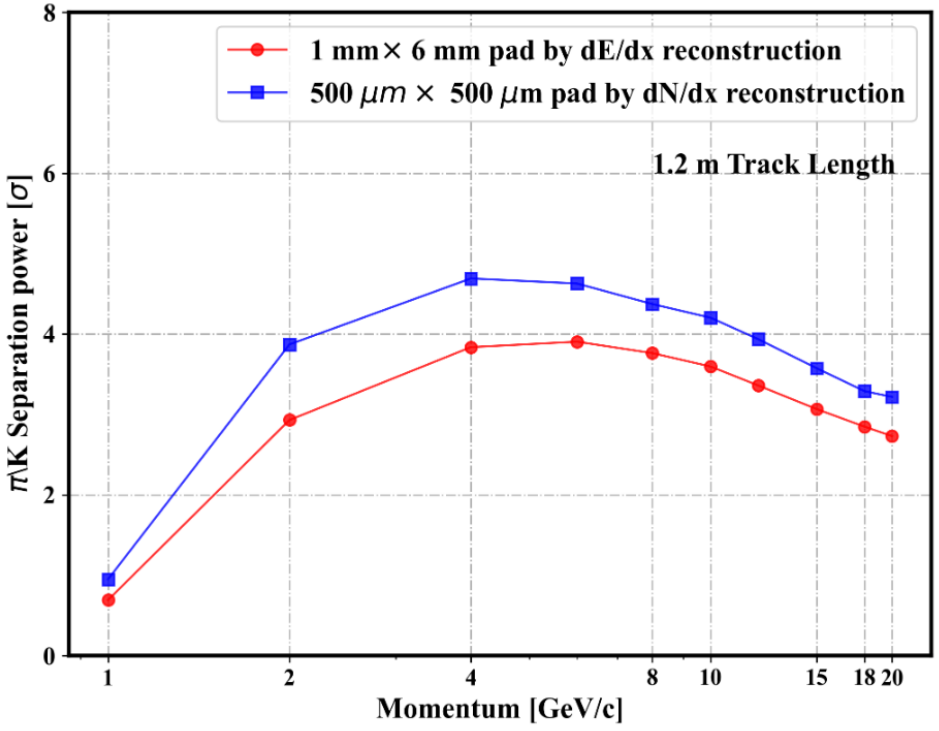
- Reconstruction by counting the number of fired pixels that pass a threshold
- Reconstruction with good linearity and reliability



Preliminary PID performance:

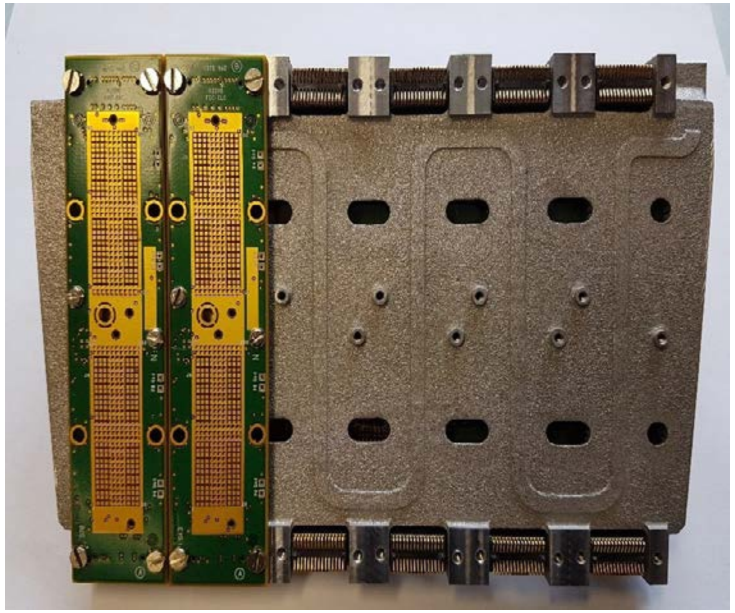
- 3σ π/k separation at 20 GeV with a 50 cm drift distance can be achieved

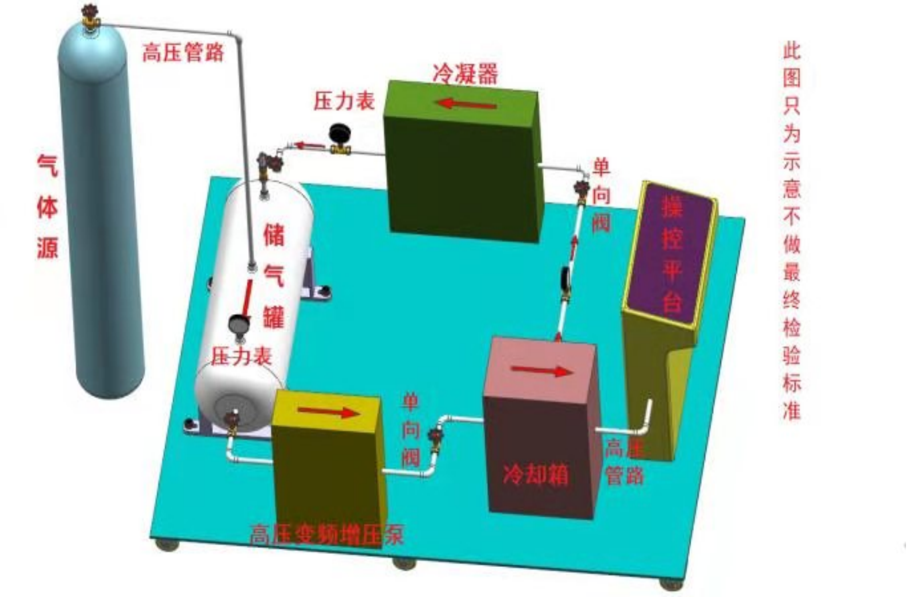
$$Sp = \frac{|\mu_A - \mu_B|}{\frac{\sigma_A + \sigma_B}{2}}$$



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 500μm×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!**)



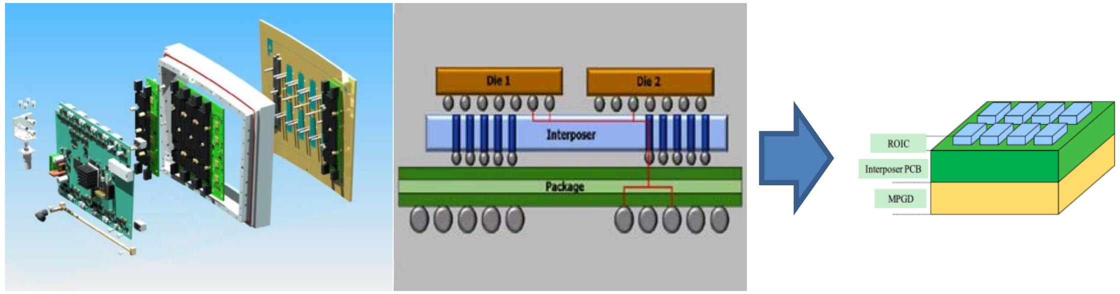


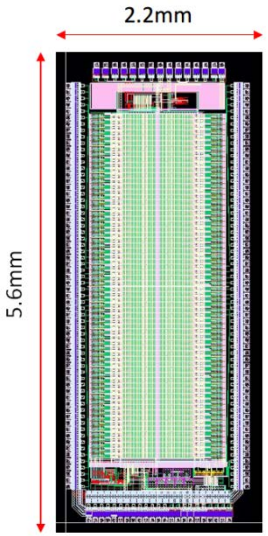
2-phase CO2 cooling for TPC module

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

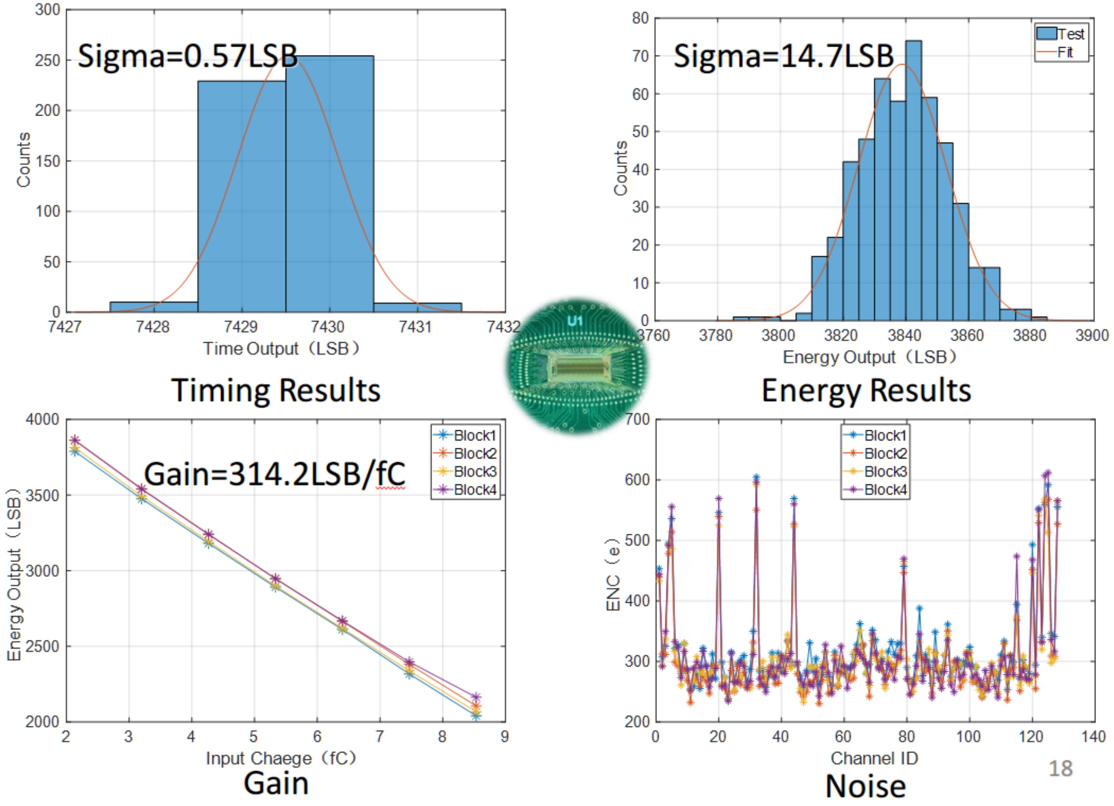
Detailed design of electronics and BEC

- 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)





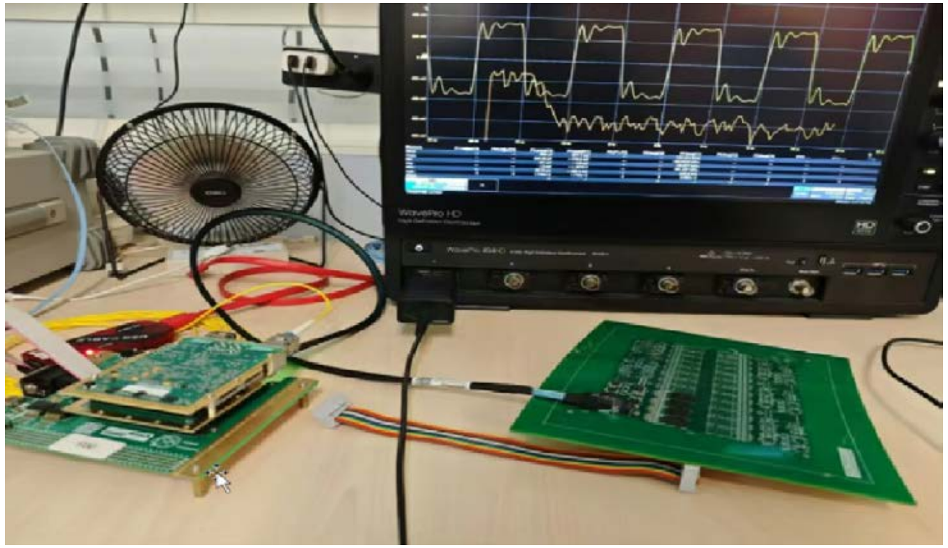
Parameter		Spec
Number of channels		128
Power Consumption		Analog<30mW
		Digital<30mW
ENC		~300 e(high gain)
Dynamic Range		25fC(high gain)
		150fC(low gain)
INL		<1%
Time Resolution		<10ns

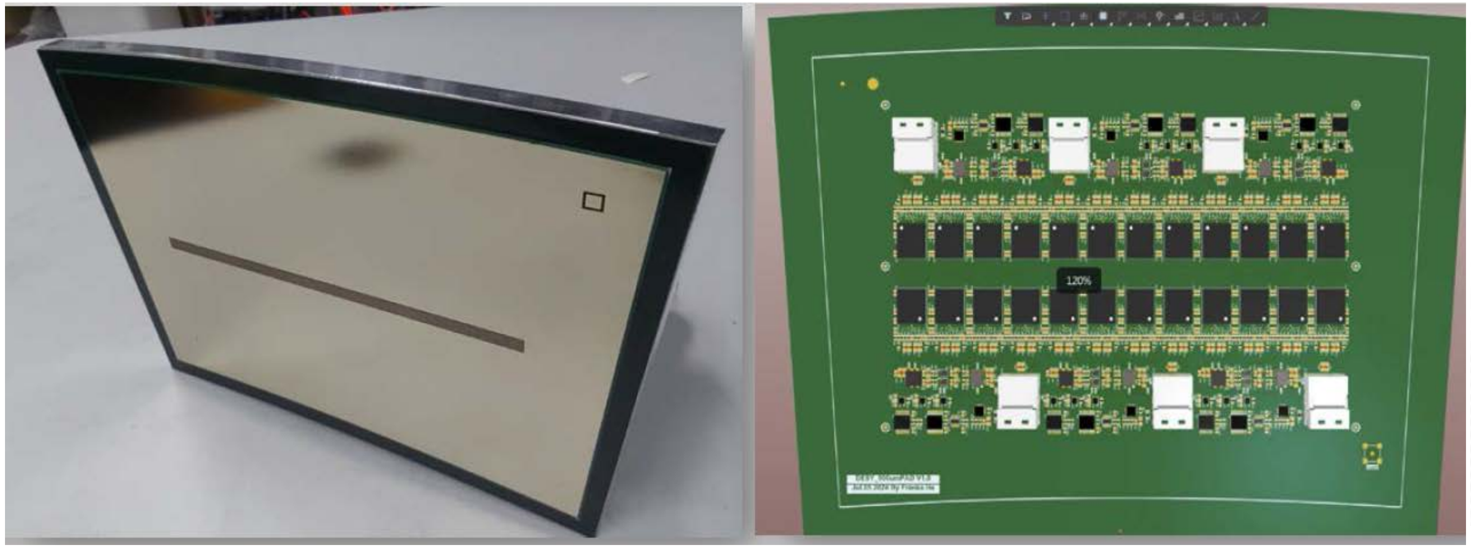


FEE ASIC: TEPIX—Test Results in May

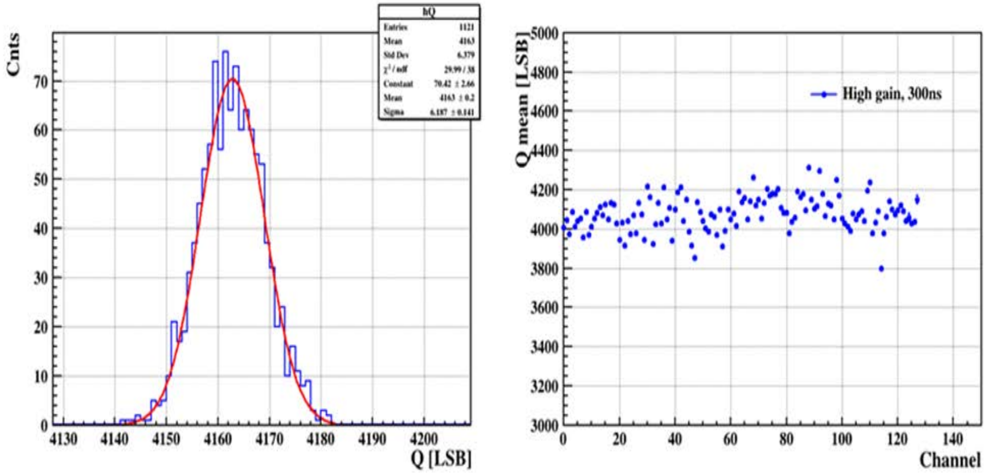
Validation and commission of TPC prototype

- **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 prototype assembled for beam test.





Photos TPC modules assembled for the beam test

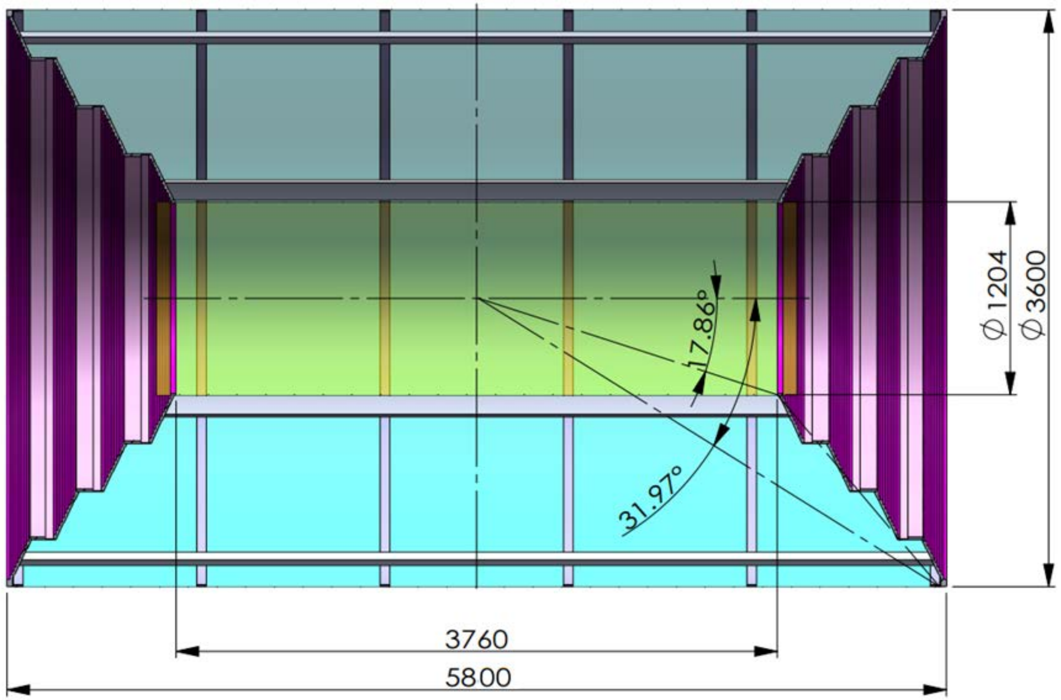


Amplitude (left) and Uniformity/ch (right)

Performance of pixelated readout TPC

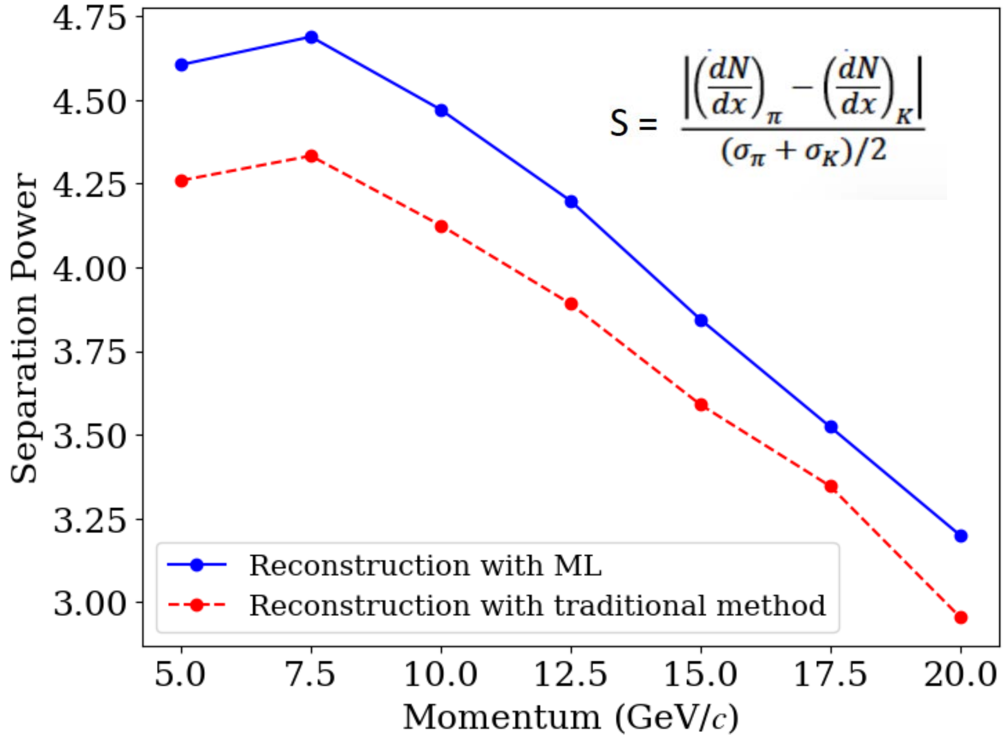
Parameters	Higgs run	Z pole run
B-field	3.0 T	2.0 T
Readout size (mm)/All channels	0.5mm×0.5mm /2×3×10^7	0.5mm×0.5mm /2×3×10^7
Layers per track in rφ	2300	2300
Material budget barrel (X_0)	0.59 %	0.59 %
Material budget endcap (X_0)	15 %	15 %
σ in rφ	120μm (full drift)	400μm (full drift) w. distortion
σ in z	≃ 0.6 - 1.0 mm (for zero – full drift)	≃ 0.6 - 1.0 mm (for zero – full drift)
2-hit separation in rφ	0.5 mm	0.5 mm
K/π separation power @20GeV	3 σ	3 σ
dE/dx	< 3.0 %	< 3.0 %
Momentum resolution normalized: $\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$	a = 1.9 e -5	a = 3.3 e -5
	b = 0.8 e -3	b = 1.5 e -3

Detailed design of DC for Tera-Z



K/π separation power vs. momentum

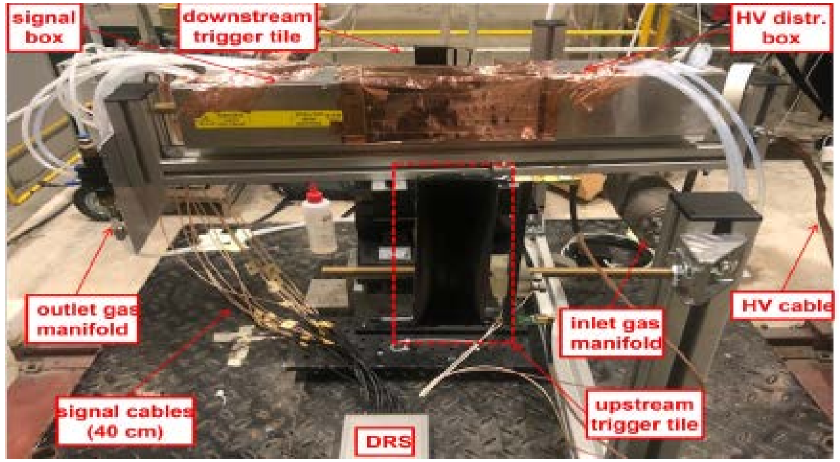
(Waveform-based full simulation)

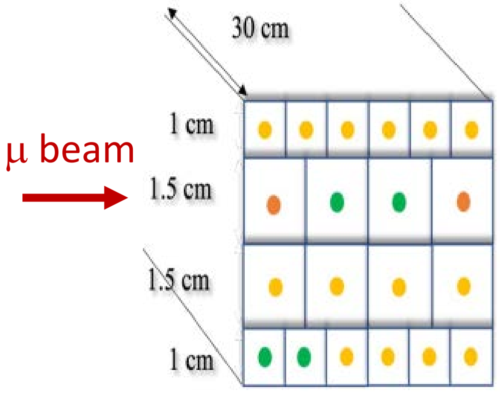


- CF frame structure
- Length: 5800 mm; Outer diameter: 3600 mm; Inner diameter: 1200 mm
- Thickness of each end plate: 20 mm, weight: 880 kg
- Gas mixture: He + iC_4H_{10} (90/10)
- Cell size: 18mm x 18mm, number of cells: 26483
- Material: 0.16% X_0 for Gas+Wires, 0.21%X_0 for inner and outer cylinders
- Finite element analysis: Endplate deformation 2.7mm, CF frame deformation 1.1mm

International collaboration of DC

- **Beam tests at CERN organized by INFN group (leaded by Franco Grancagnolo and Nicola De Filippis)：**
- **Cooperation on**
  - Data taking
  - Data analysis
  - Reconstruction algorithm study

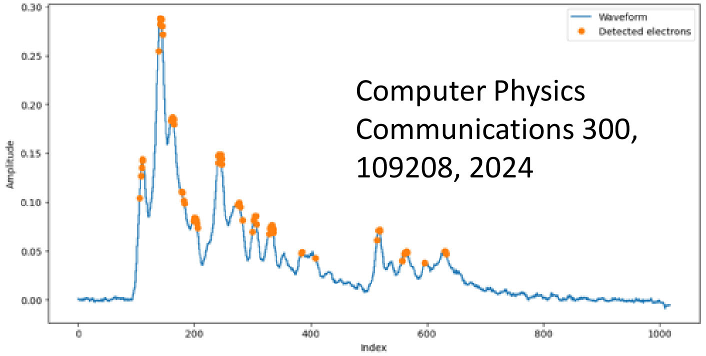




He + iC_4H_{10}
90/10, 85/15, 80/20

- 15μm (Mo+Au)
- 20μm (W+Au)
- 25μm (W+Au)

Waveform reconstruction with ML (domain adaptation)



Computer Physics Communications 300, 109208, 2024

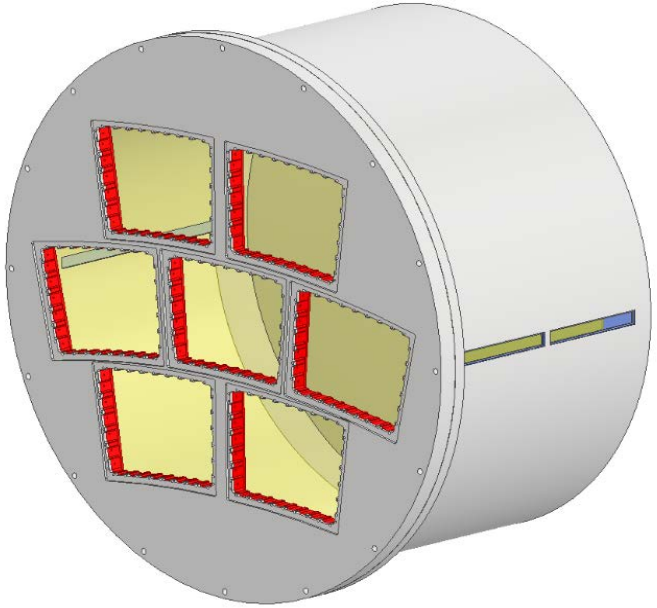
Research Team

- Core of the research team (**10 staffs + TPC group**)
  - IHEP: Huirong Qi, Linghui Wu, Guang Zhao, Mingyi Dong, Yue Chang, Xin She, Jinxian Zhang, Junsong Zhang
  - Tsinghua: Zhi Deng, Canwen Liu, Guanghua Gong, Feng He, Jianmeng Dong, Yanxiao Yang
- Collaboration of the research team (**6 staffs +10 students + 5 LCTPC members**)
  - **TPC:** CIAE, Shandong University, Nankai University, Zhengzhou University and Liaoning University
  - **DC:** Wuhan University, Jilin University
  - **TPC and DC**: DRD1 collaboration and LCTPC collaboration
- Organization of team
  - Regular weekly meeting from April 2024
  - Collaboration regular meeting with some international groups

Shared editing chapter from overleaf

Working plan

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



- Long term working plan (**next 3-5 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.**

Thank you for your attention!

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