



# Update Status of the Baseline Gaseous Tracker Technology in the CEPC TDR

**Huirong Qi**

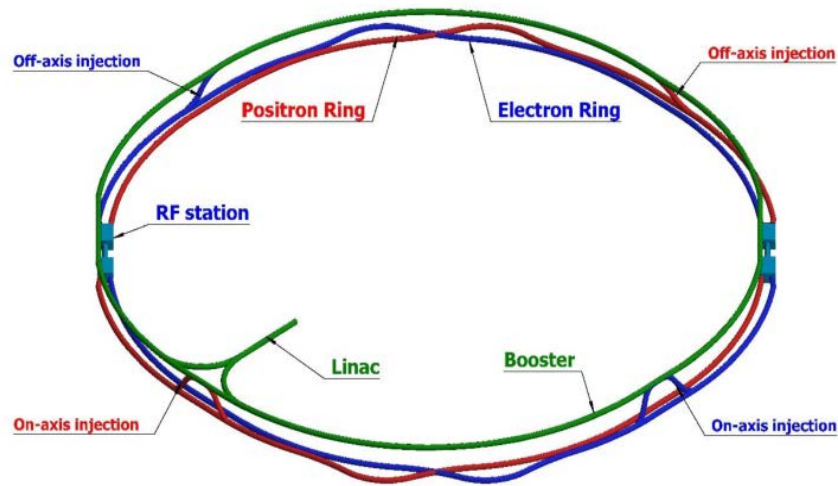
**On behalf of the gaseous tracker group  
and some inputs from LCTPC international collaboration**

# Content

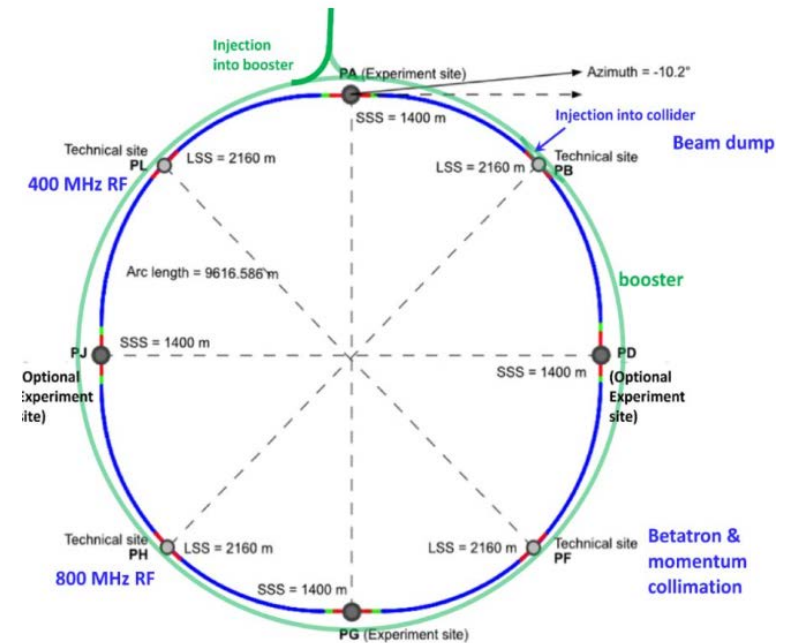
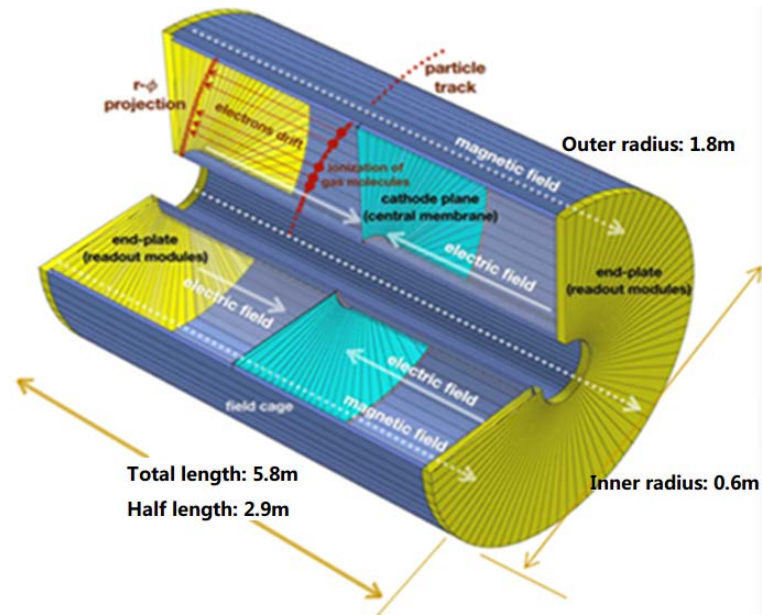
- **Motivation and physics requirements**
- **Technical challenges and R&D efforts**
- **Detail design of CEPC TPC**
- **Simulated performance**
- **Summary**

# Motivation on $e^+e^-$ collider

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



Circular Electron Positron Collider (CEPC)



Future Circular Collider (FCCee)

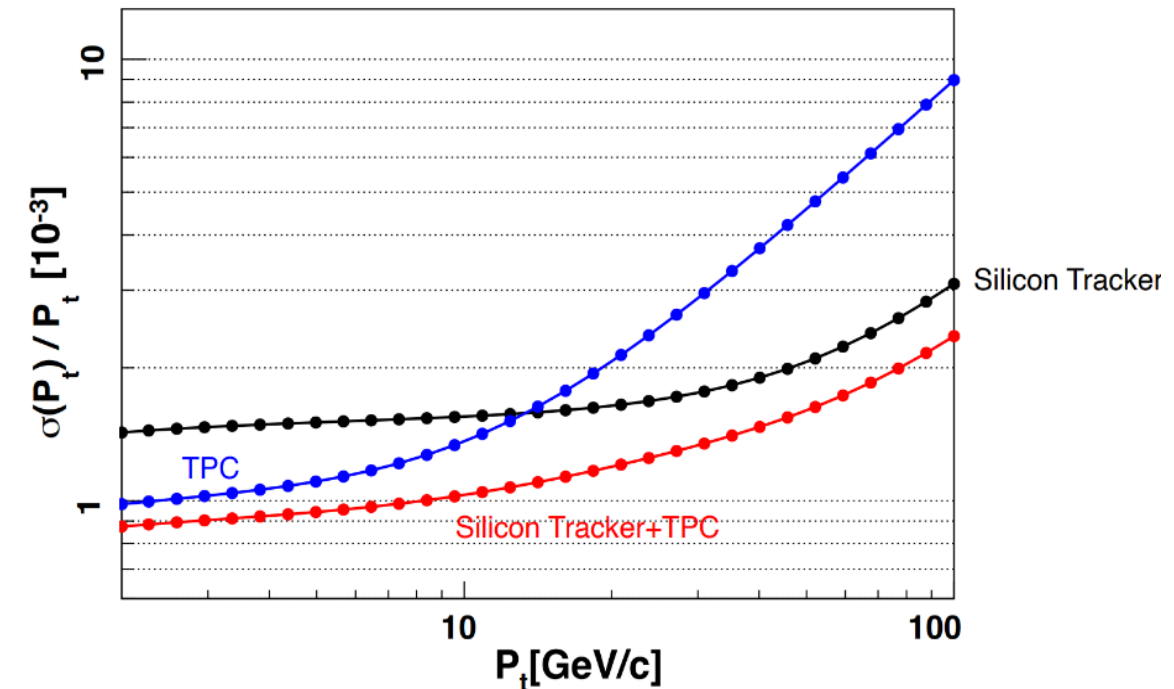
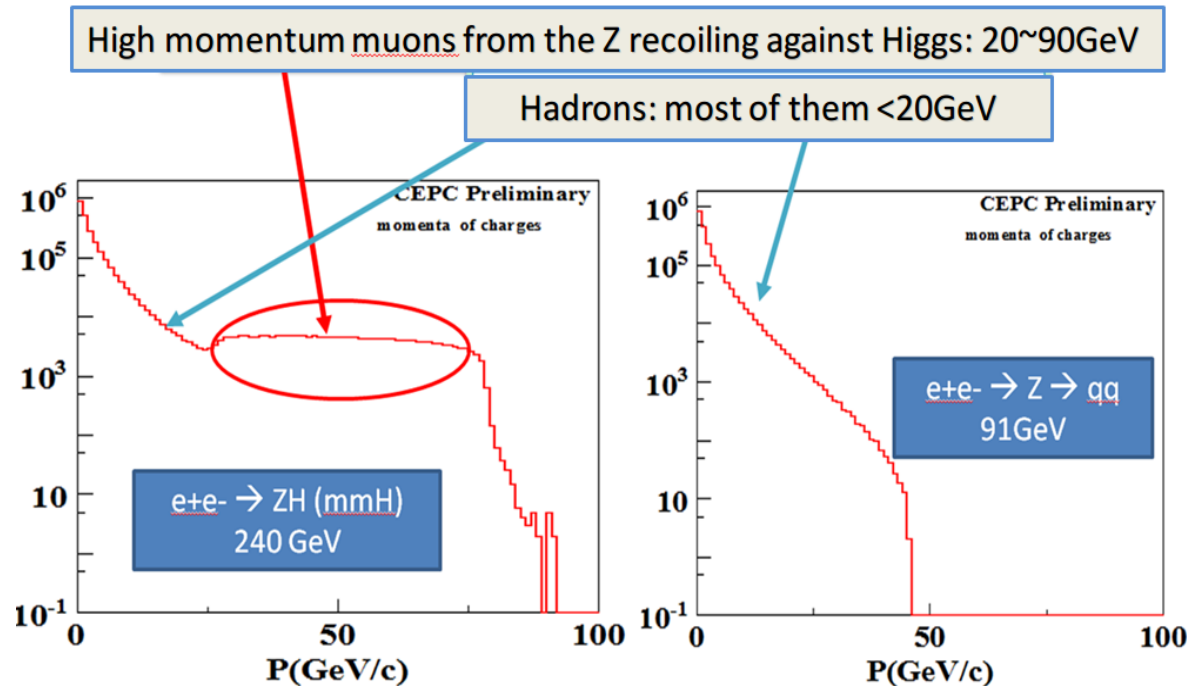
# Physics requirements

■ CEPC operation stages in the TDR: **10-years Higgs** → **2-years Z pole** → **1-year W**

■ Physics Requirements of the tracker

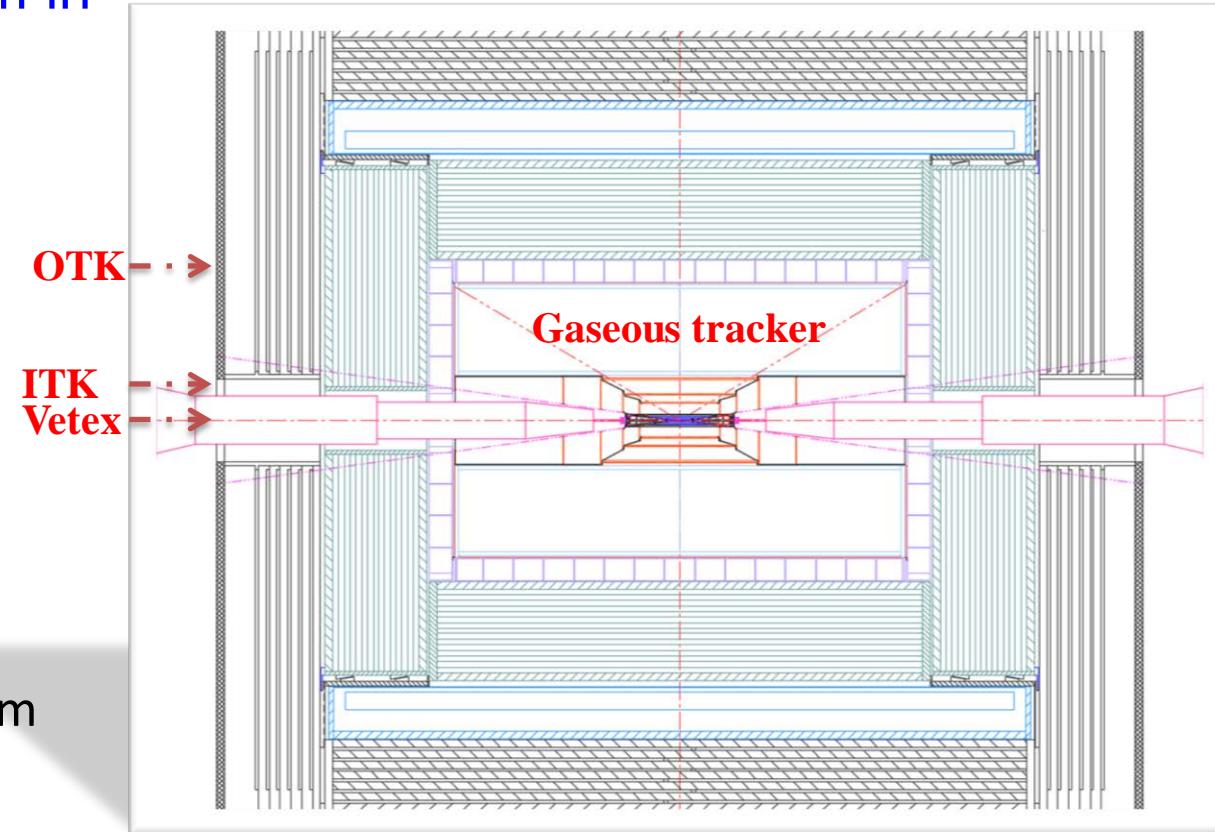
- High momentum resolution for Higgs and Z
- PID for the flavor physics and jet substructure

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



# Large gaseous tracker

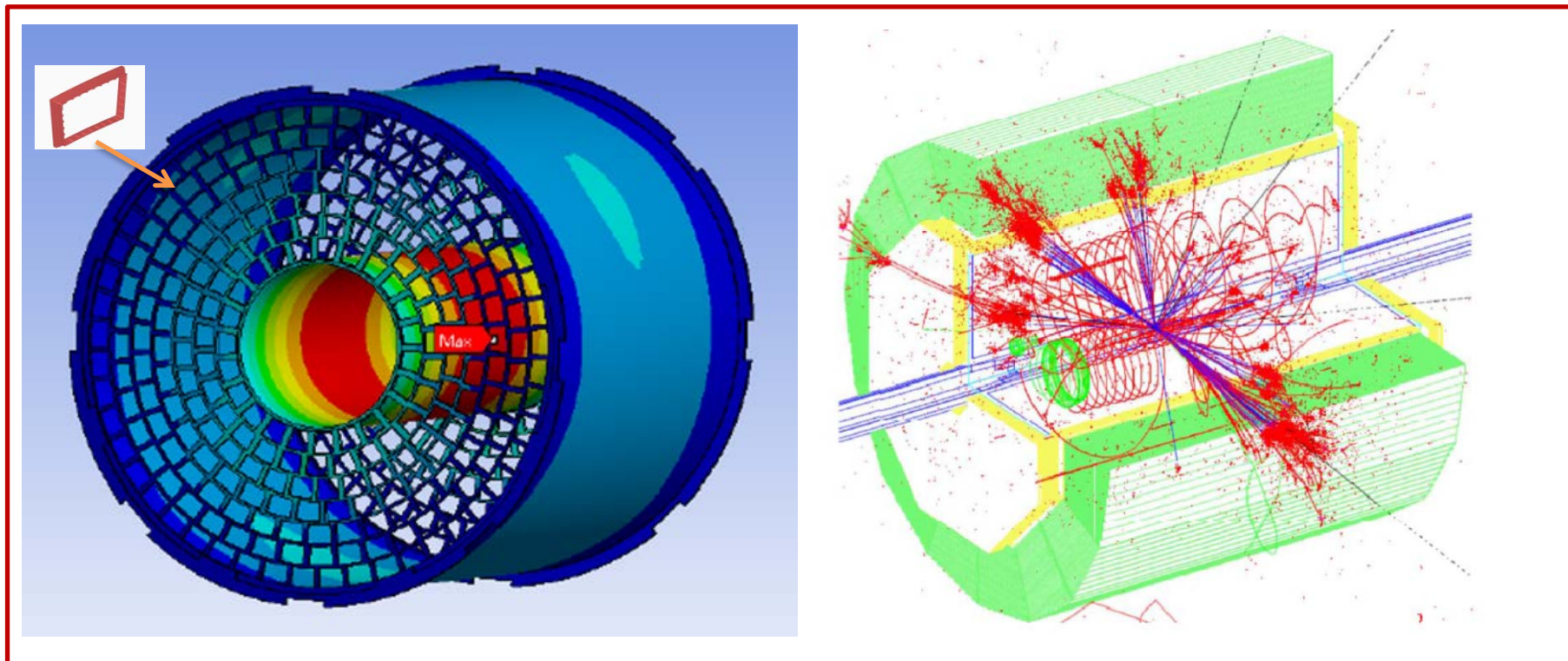
- The detector adopts a hybrid tracking system in CEPC ref-TDR.
- Large gaseous tracker
  - PID of charged hadrons:
    - Benefit flavor tagging and jet substructure study
    - Reduce combination background
  - Quasi-continuous tracking: track finding
  - Ultra light material budget
    - Improved performance at the low momentum ( $<15\text{GeV}/c$ )
    - The total materials ( $\sim 0.65\% X_0$ ) is equivalent to **about 1 layer of a silicon tracker detector**.



Schematic diagram of the detector

# TPC Detector Technology

- Precision 3D track reconstruction with Ultra light material budget
  - High spatial resolution ( $\sim 100\ \mu\text{m}$ ) with thousands of hits per track
  - High precision tracking and High **Particle Identification** resolution ( $\sim 3\%$ )
  - Operation at **Higgs (3T) and Tera-Z (2T)**; Modular design and easy to install
- Considering the technical challenges, detector performance, and risk in constructing the detector

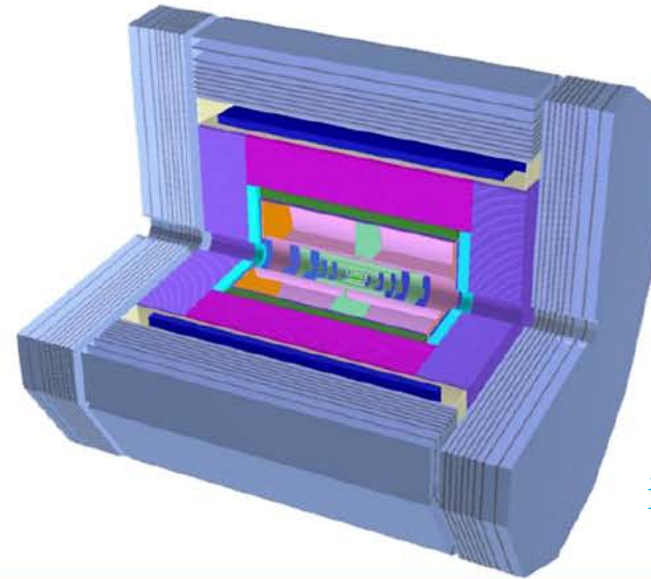


Time Projection Chamber

# Status of TPC in LCTPC and CEPC

- January 2024, the CEPC community initiated the technical comparison and selection, balancing factors including **R&D efforts, detector performance, cost, power consumption and construction risks.**

System	Technologies	
	Baseline	For comparison
Beam pipe	Φ20 mm	
LumiCal	SiTrk+Crystal	
Vertex	CMOS+Stitching	CMOS Pixel
Tracker	CMOS SiDet ITrk	
	Pixelated TPC	PID Drift Chamber
	AC-LGAD OTrk	SSD / SPD OTrk
		LGAD ToF
ECAL	4D Crystal Bar	PS+SiPM+W, GS+SiPM, etc
HCAL	GS+SiPM+Fe	PS+SiPM+Fe, etc
Magnet	LTS	HTS
Muon	PS bar+SiPM	RPC
TDAQ	Conventional	Software Trigger
BE electr.	Common	Independent



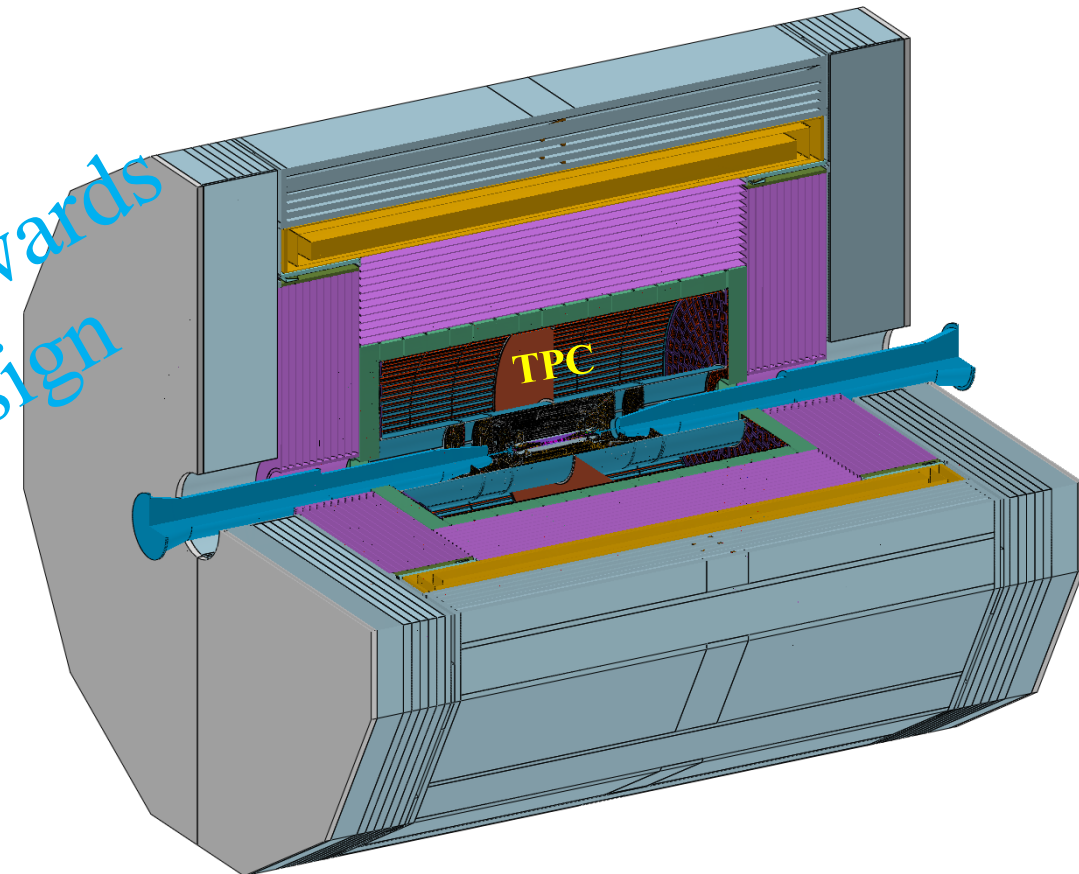
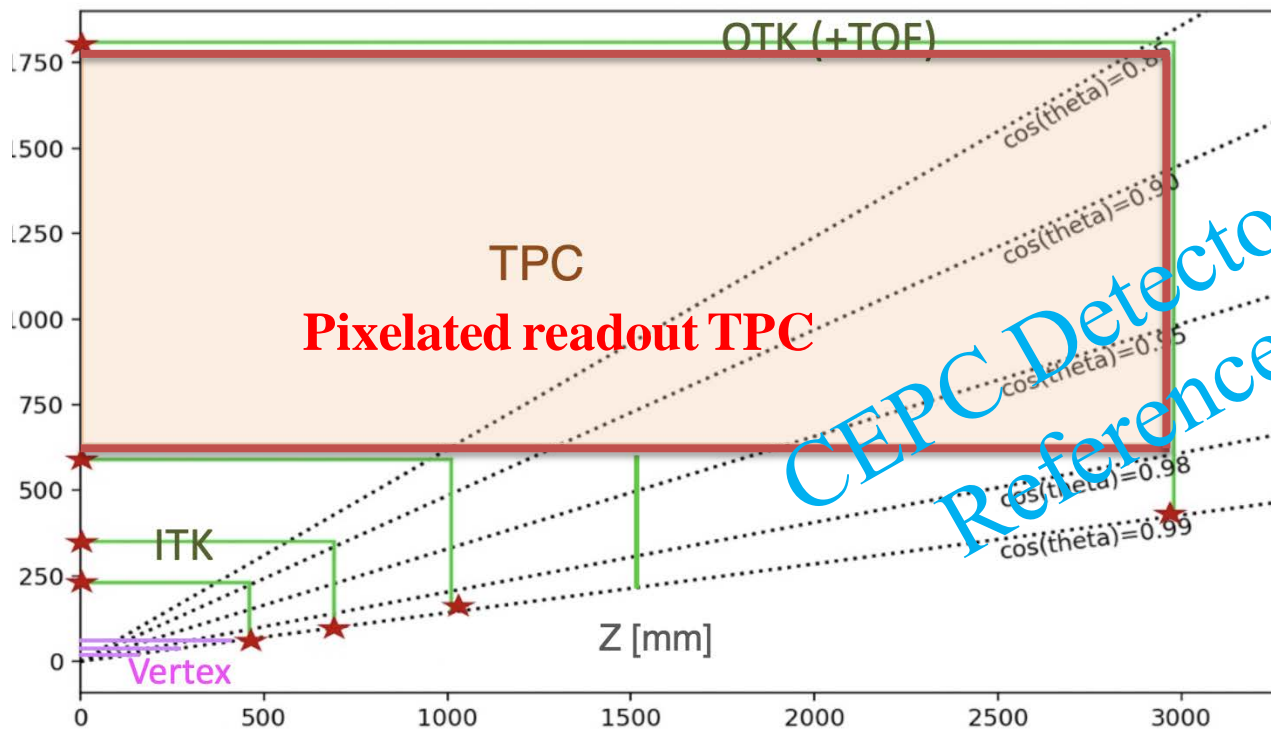
Jianchun Wang's talk  
in CEPCWS at Hangzhou.

## Foundations:

- CEPC Instrumentation R&D
- LHC detector upgrade projects
- other HEP experiments
- progress in HEP worldwide R&D
- development in industry

# Baseline gaseous detector: Pixelated TPC

- Tracking system: Silicon combined with gaseous chamber for the tracking and PID
  - Pixelated readout TPC as the **baseline gaseous detector** in the CEPC ref-TDR.
    - Radius of TPC from 0.6m to 1.8m



Geometry of the tracking detector system of the CEPC TDR

# Main Technical Challenges

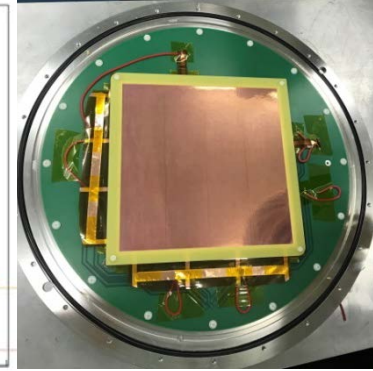
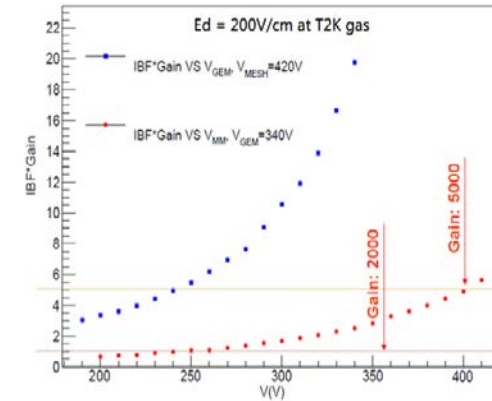
- **Pixelated readout TPC gaseous tracker**

**Critical key  
items**

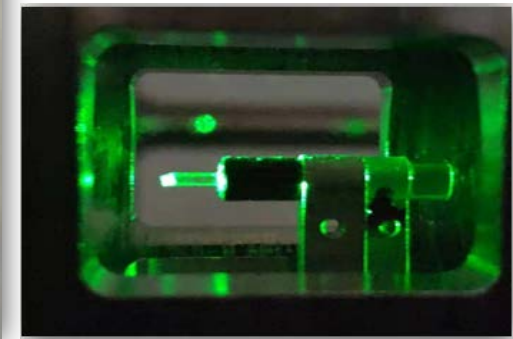
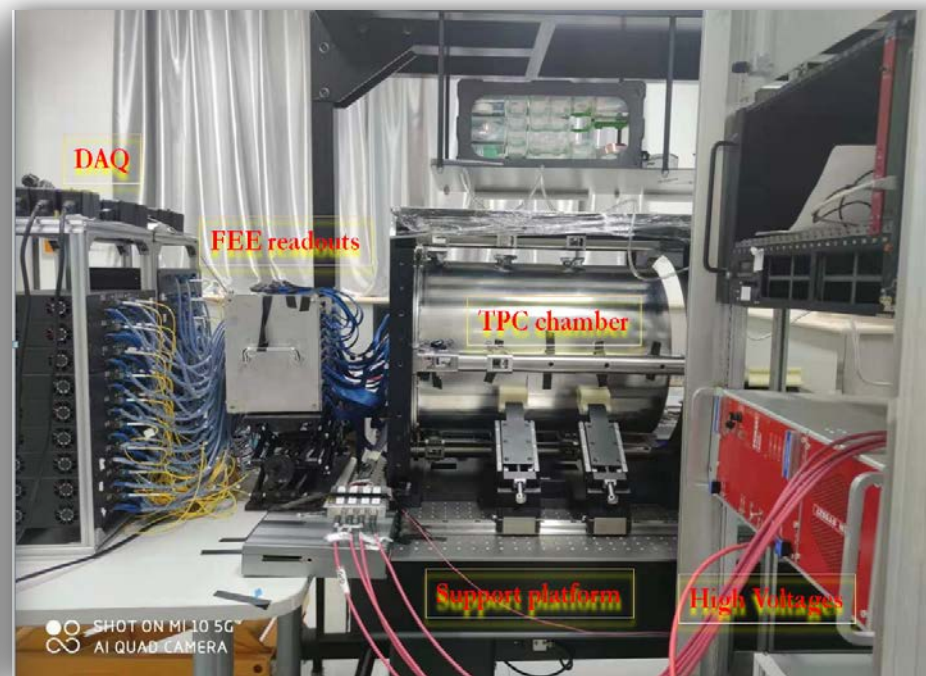
- **Material budget at endcap/barrel ✓**
- **Occupancy and hit density at Tera-Z ✓**
- **Ion backflow suppression ✓**
- **To meet the PID requirement ✓**
- **Optimization of number of channels (ongoing)**
- **Acceptable power consumption (ongoing)**

# 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 so far:
  - **$IBF \times Gain \sim 1$  @  $G=2000$**  validation with a hybrid TPC module
  - Spatial resolution of  **$\sigma_{r\phi} \leq 100 \mu m$  and  $dE/dx$  resolution of 3.6%**
  - FEE chip: reach  **$\sim 3.0 mW/ch$  with ADC** and the pixelated readout R&D

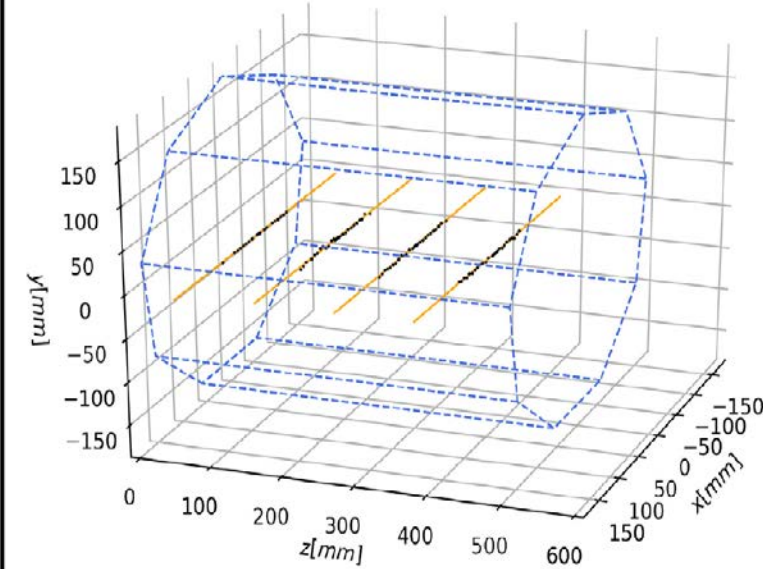
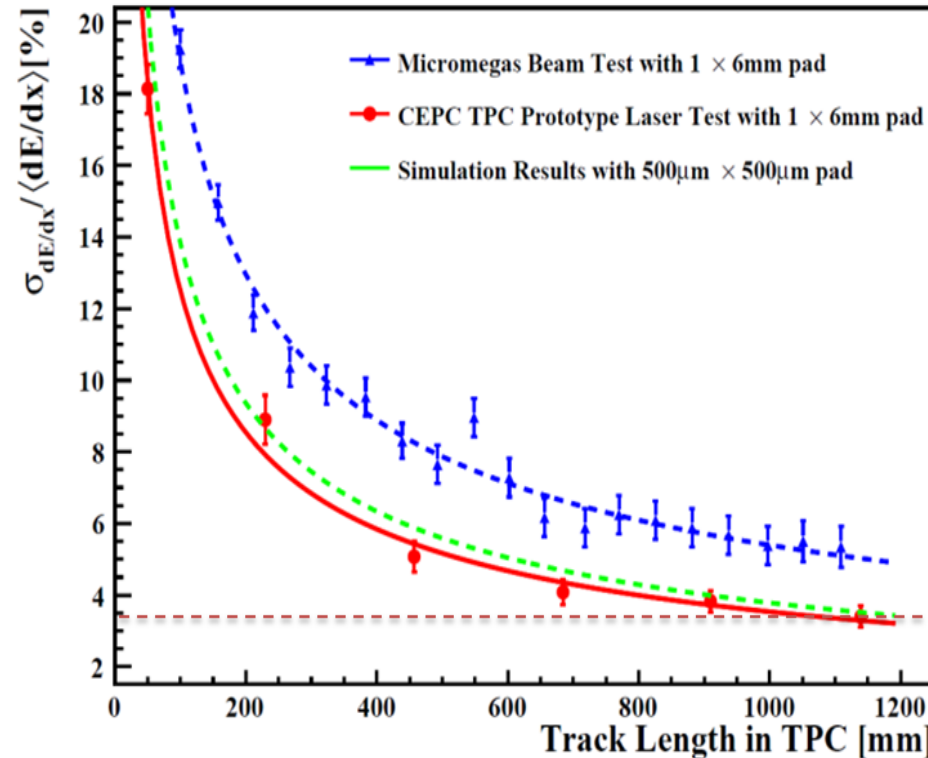
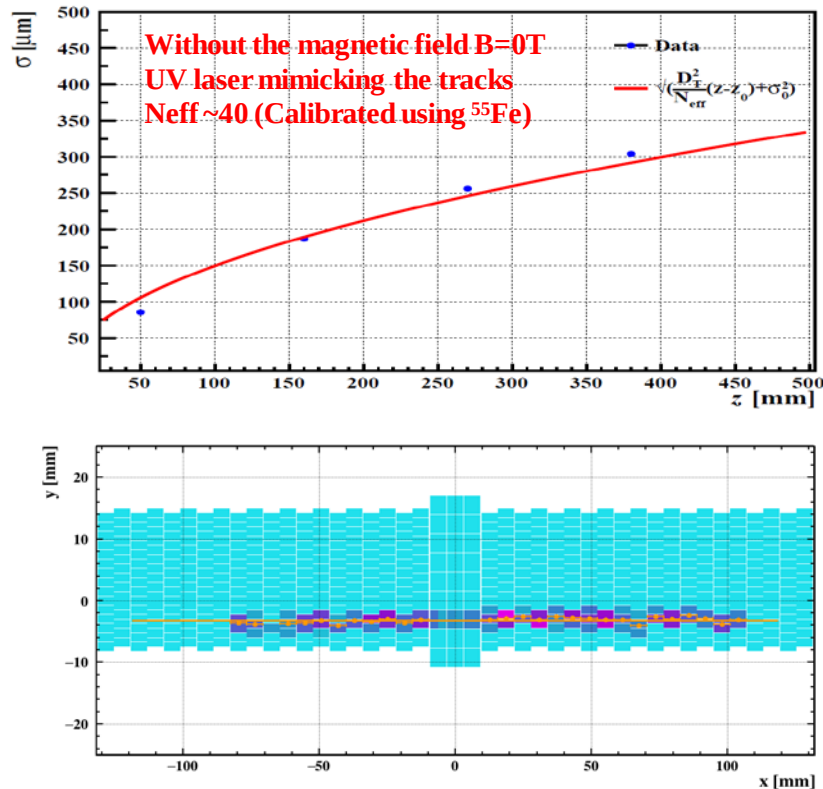
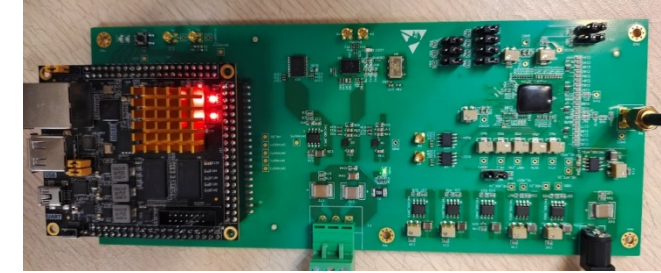


Ion suppression TPC module R&D



# Highlights of TPC prototype R&D

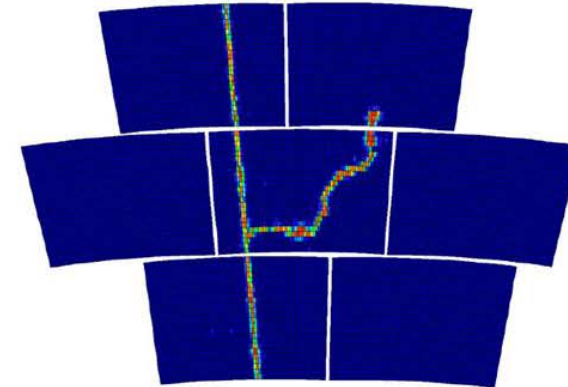
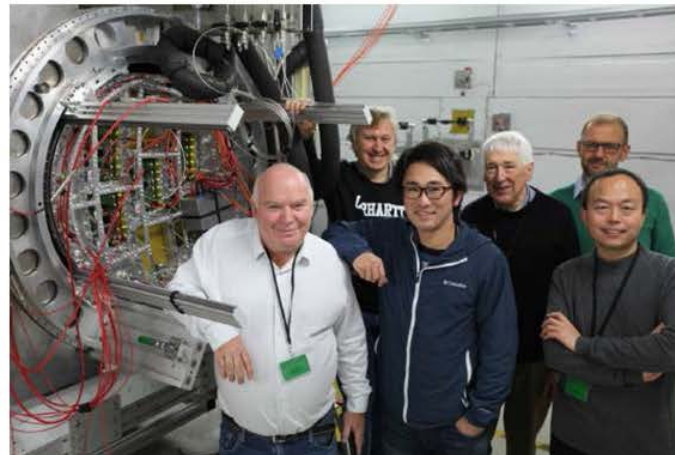
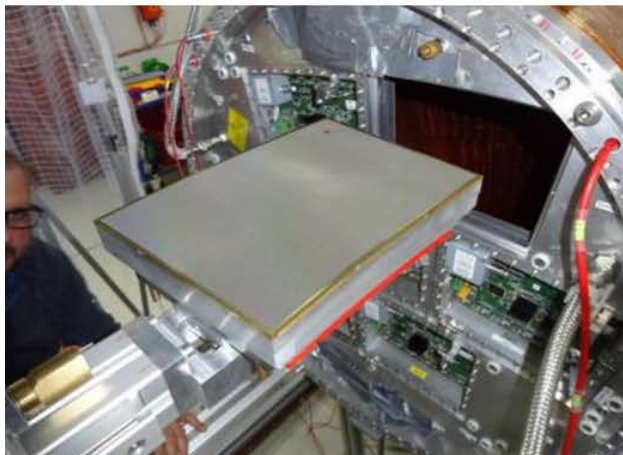
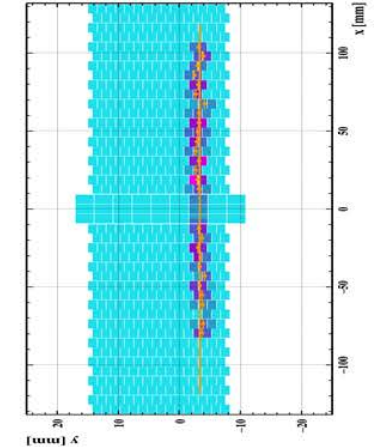
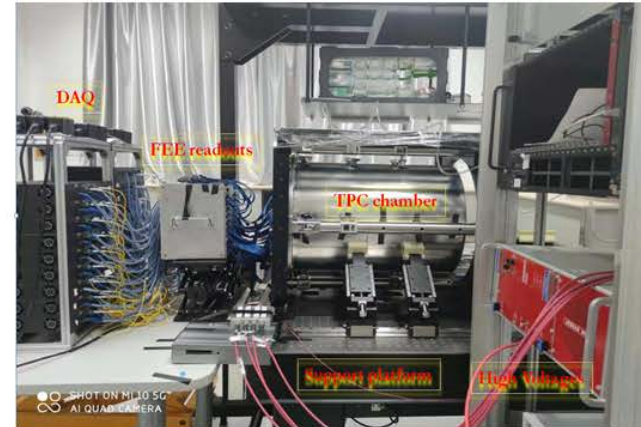
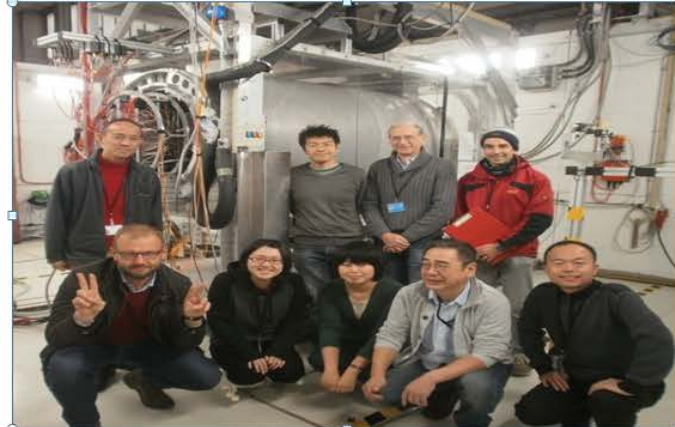
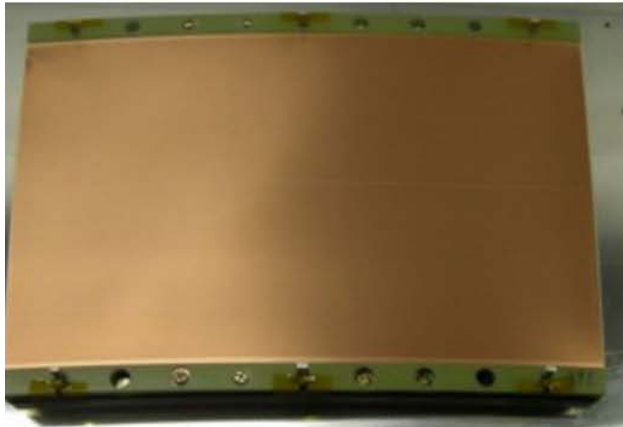
- Highlights of R&D of CEPC pad-readout TPC, and toward **pixelated-readout TPC**
  - A lab for MPGD assembly and mass production has been set up at IHEP.
  - A TPC prototype integrated 266nm UV laser tracks has been constructed. The UV laser signals are analyzed, proving that the TPC is good for the Higgs run.
  - **Easy-to-install modular design** of Pixelated readout TPC for CEPC TDR.



# Active international collaboration

- **Active 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  $\varnothing$ : 85cm, Spatial resolution of  $\sigma_{r\phi} \leq 100 \mu m$
  - Collaboration implement improvements in **a pixelated readout TPC for CEPC TDR**

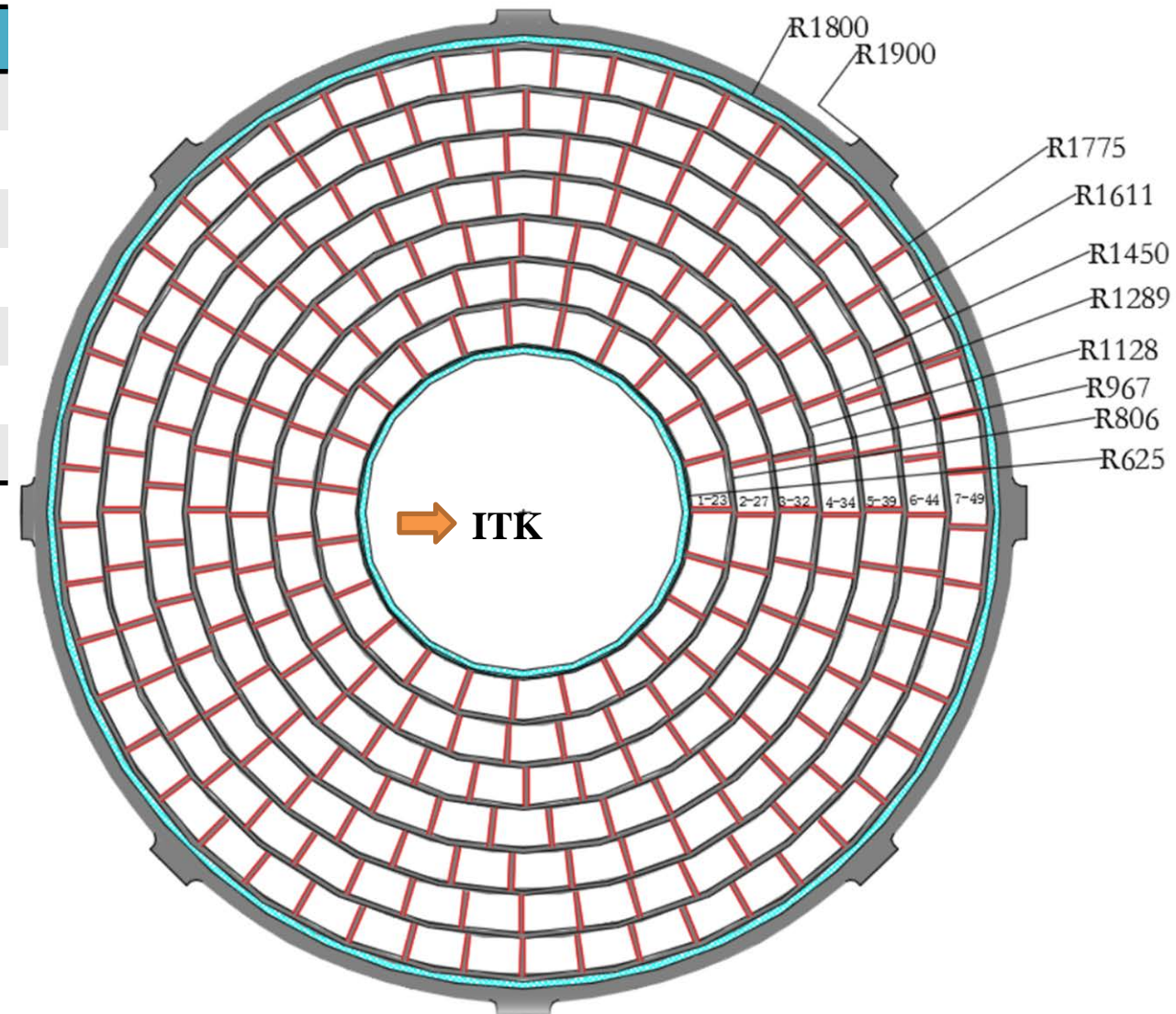
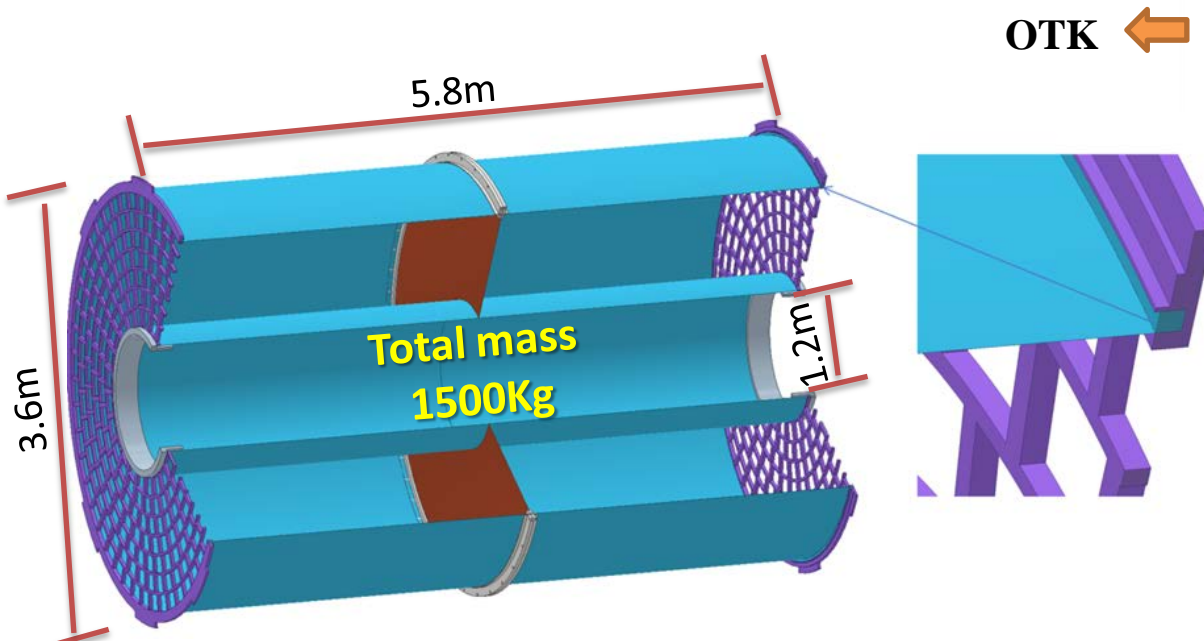
ArXiv. (2023)2006.08562  
NIM A (2022) 167241  
ArXiv (2022)2006.085  
JINST 16 (2021) P10023  
JINST 5 (2010) P10011  
NIM A608 (2009) 390-396



# **Detailed design and performance of The Baseline: TPC**

# Detailed design of mechanics

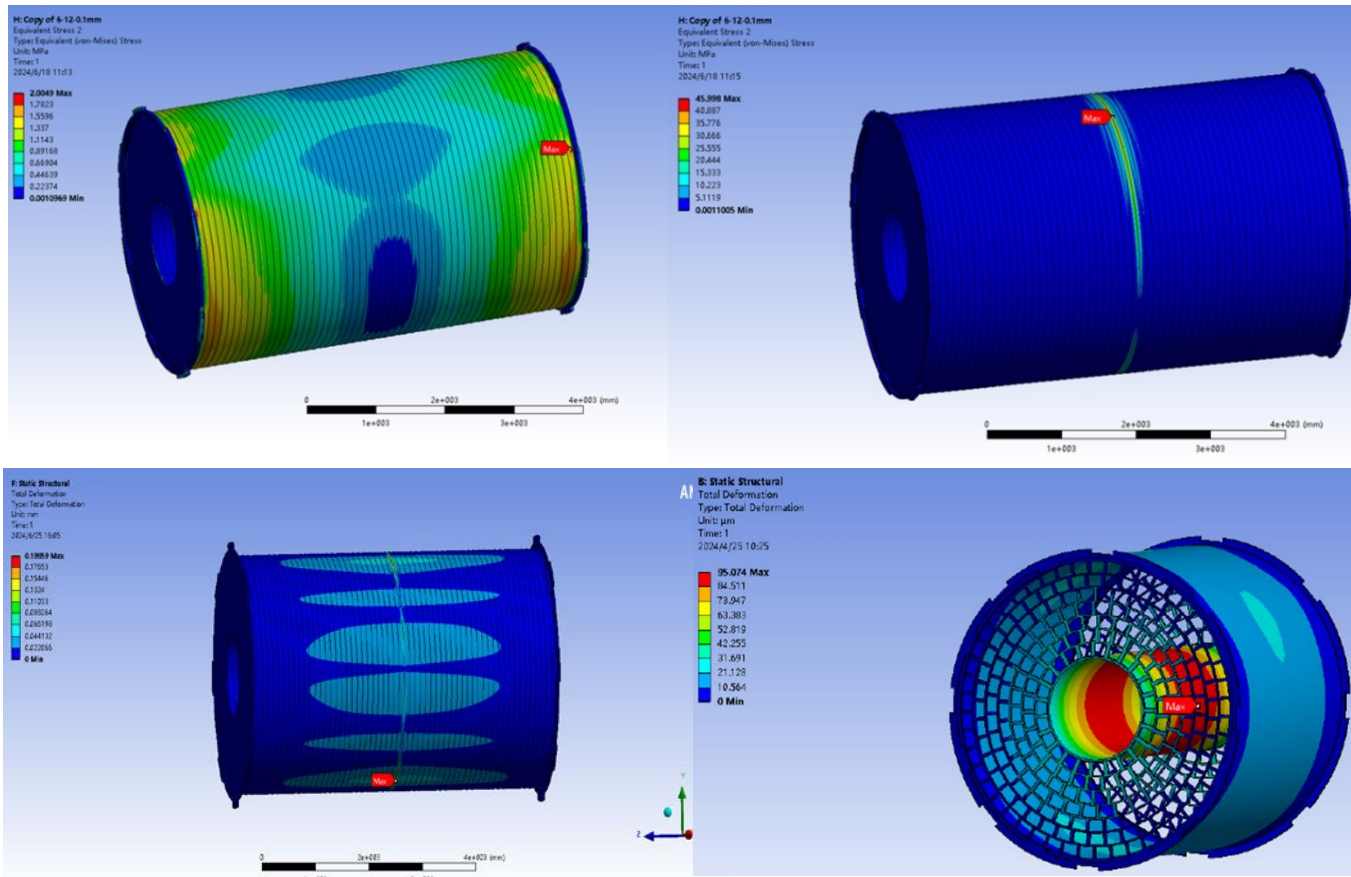
TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Module size	206mm × 224mm × 161mm
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF <sub>4</sub> /iC <sub>4</sub> H <sub>10</sub> =95/3/2
Maximum drift time	34μs @ 2.75m
Detector modules	Pixelated Micromegas



Detailed design of TPC detector in ref-TDR

# Ultra-light barrel and FEA analysis

- Consideration of new the **Carbon Fiber** barrel instead of the honeycomb barrel ( $\sim 2\% X_0$ )
- **Ultra-light material** of the TPC barrel (QM55 CF) : **0.59%  $X_0$  in total, including**
  - FEA preliminary calculation: 0.2mm carbon fiber barrel can support OTK ( **$\sim 200\text{Kg}$** )
- Optimization of the connection-back-frame of the endcap (on going)



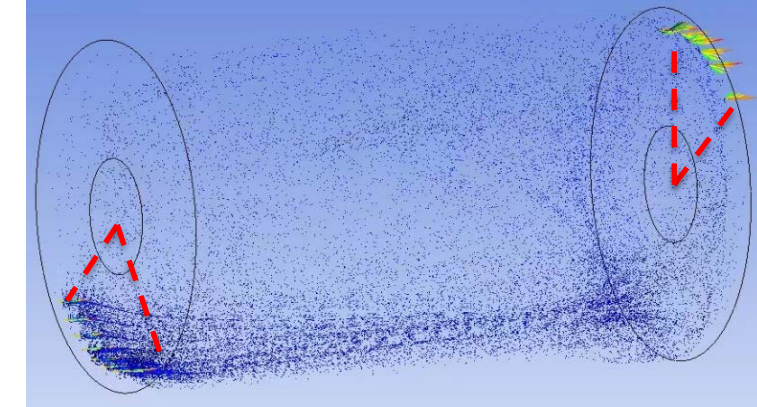
Material budget of TPC barrel

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

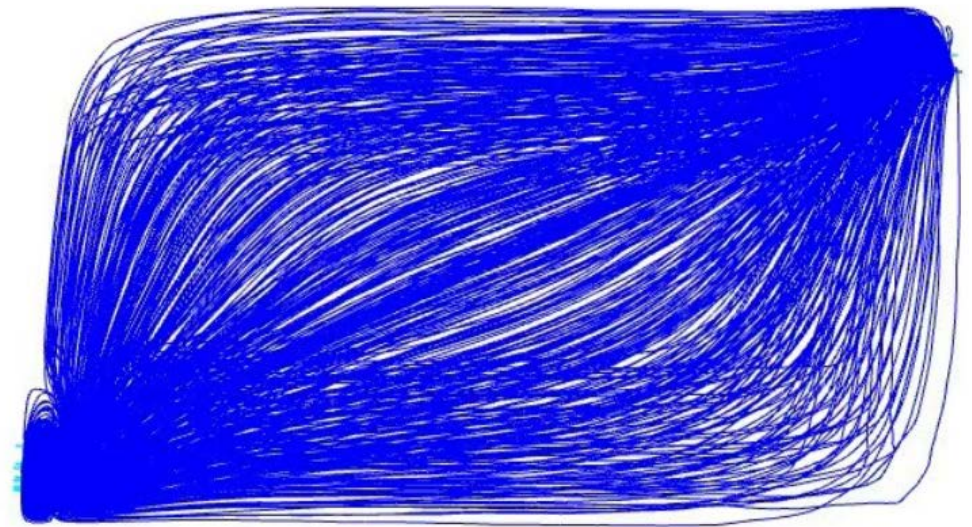
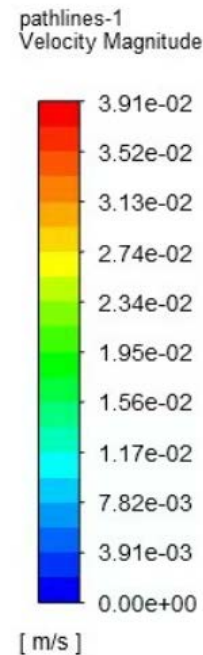
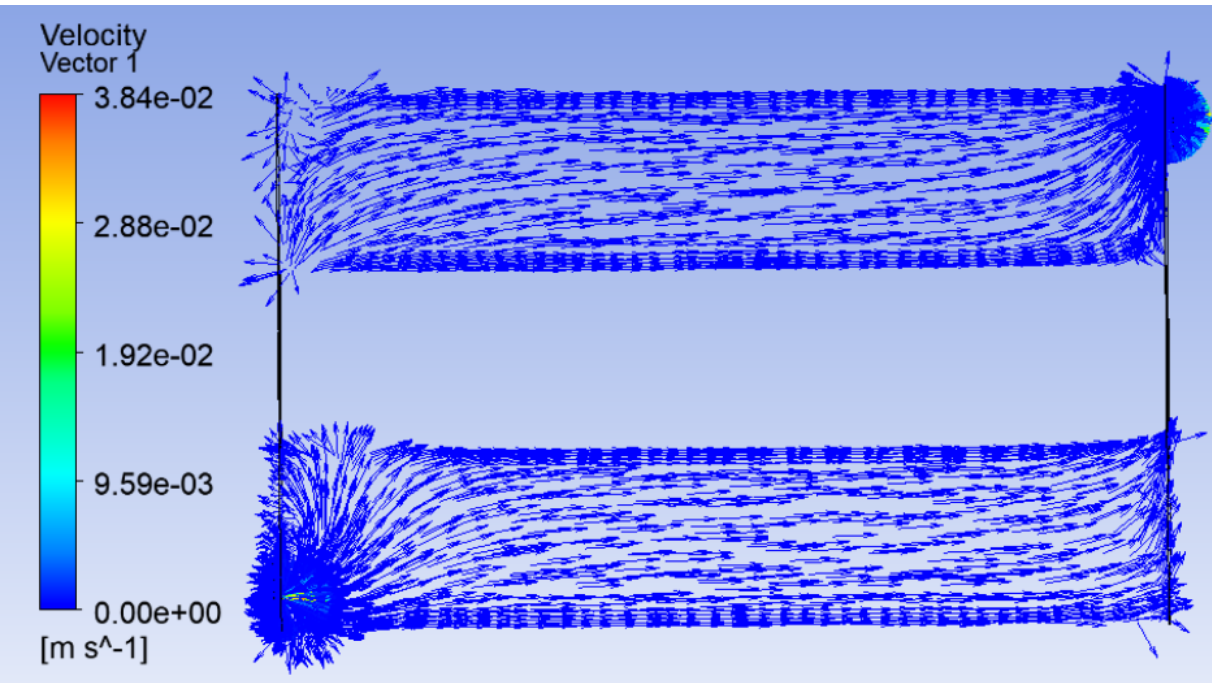
- **Low material of the TPC endcap**  
 $15\% X_0$  in total, including
  - Readout plane, front-end-electronics 4%
  - Cooling 2%
  - Power cables 9%

# Optimization of Gas flow in the Chamber

- Uniformity of gas distribution **higher than 99%** in large TPC chamber
  - **8 Ø10mm** gas inlets + **8 Ø10mm** gas outlets (opposite, 90°/endcap)
  - Working Gas Flow: 0.3 – 0.5 L/min
  - Eco-friendly gas and the **gas recycling system** also considered.
    - Online monitoring system: O<sub>2</sub> (ppm) and H<sub>2</sub>O (ppm)



Optimized inlet and outlet in Chamber



Simulation of gas flow and uniformity distribution in TPC Chamber

# Full Simulation of Pixelated readout TPC

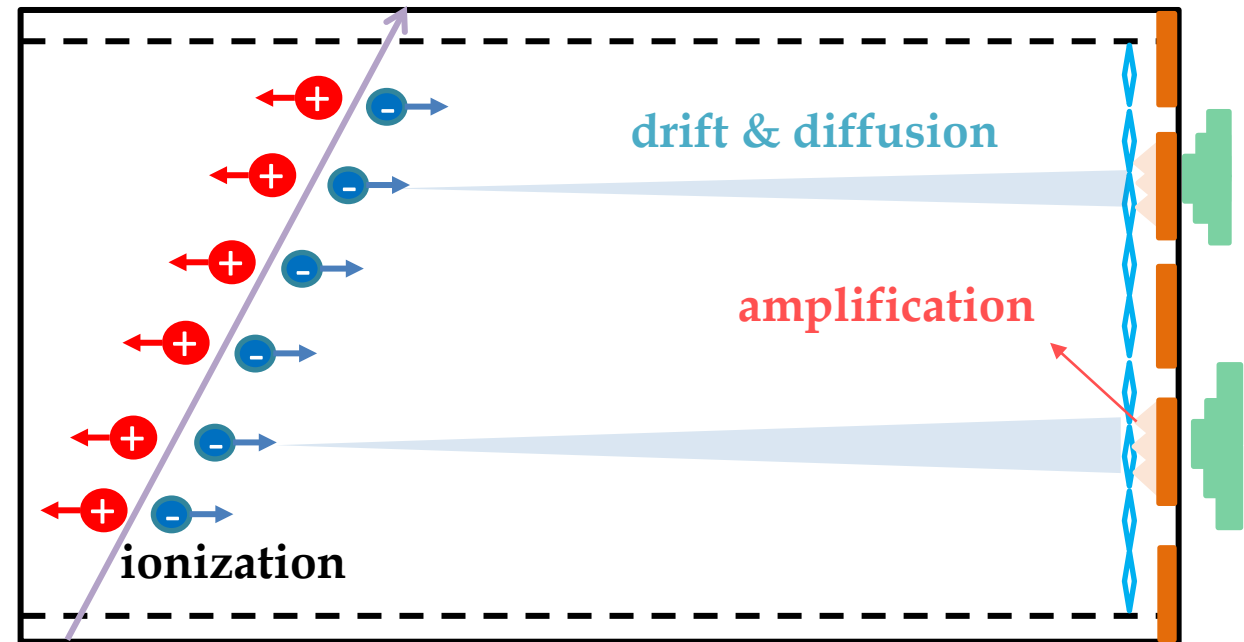
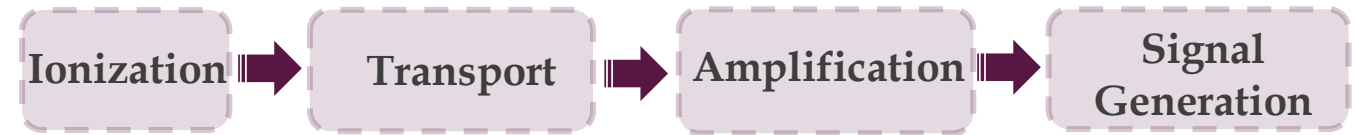
## Simulation:

- With the full TPC geometry
- Ionization simulated with Garfield++
- Drift and diffusion from parameterized model based on Garfield++

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

- Electronic noise: 100 e<sup>-</sup>
- Amplification:
  - Number of electrons: 2000
  - Profile of signal size : 100 μm

## Simulation/ Digitization Framework



Pixelated readout

# Performance of the pixelated readout TPC

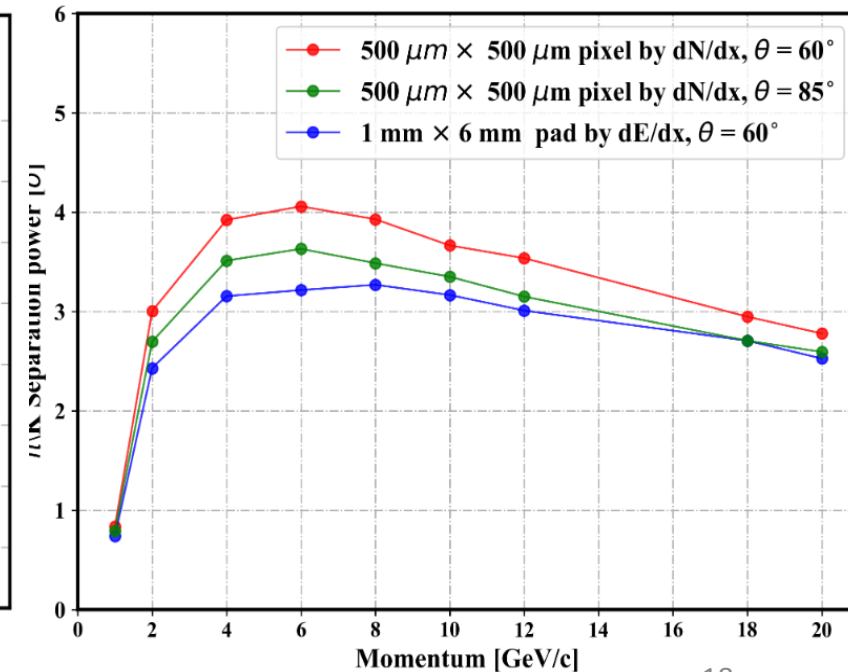
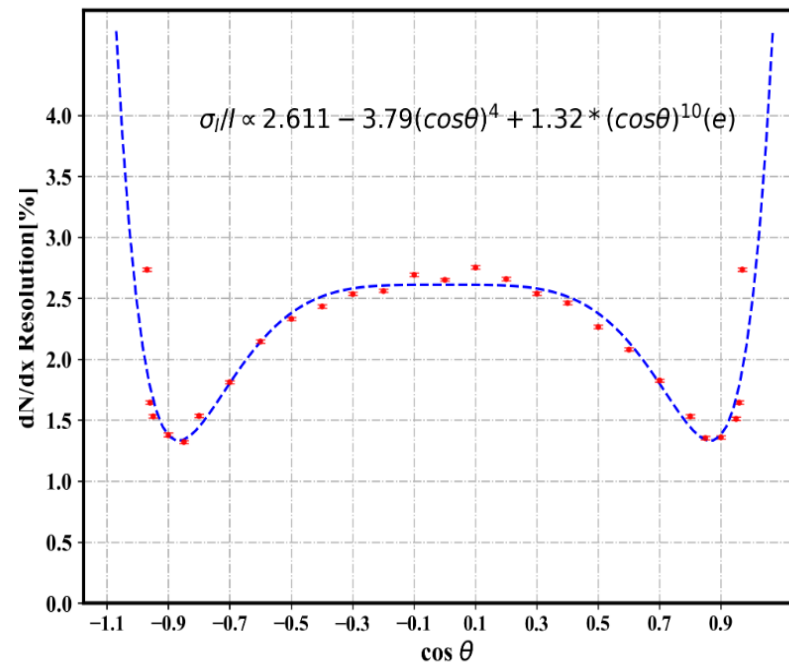
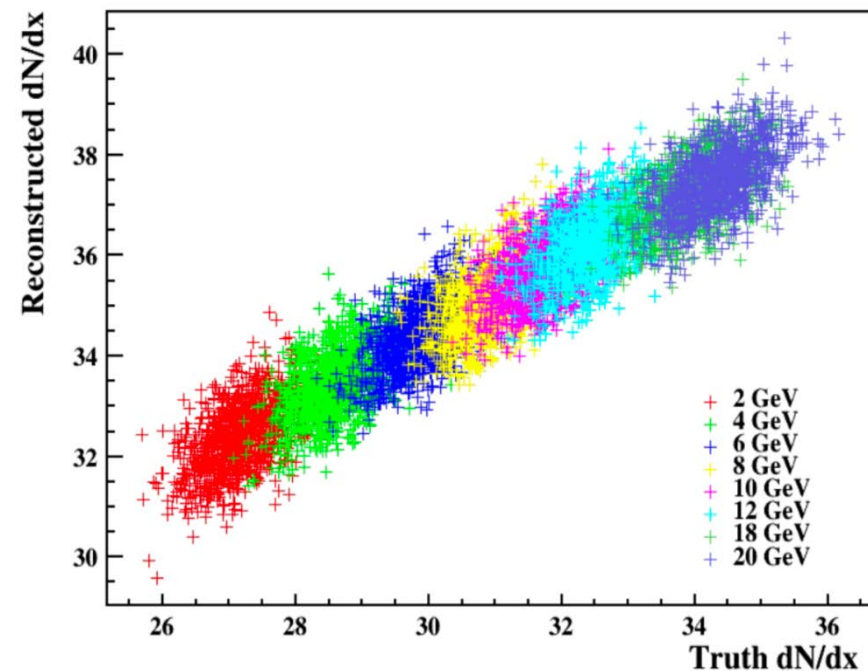
## Reconstruction:

- Reconstruction by counting the number of fired pixels over threshold
- **Reconstruction with good linearity and reliability**

## Preliminary PID performance:

- $\pi/k$  separation power simulation with different momentum

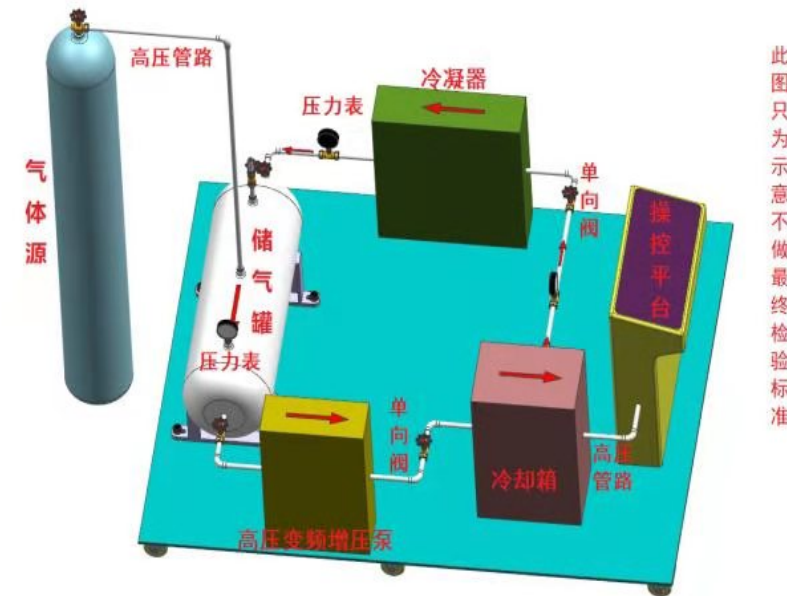
$$\text{Separation power: } \frac{|\mu_A - \mu_B|}{\frac{\sigma_A + \sigma_B}{2}}$$



# Optimization of the readout size

- Timepix (55μm×55μm) readout TPC prototype has been validated four times using DESY beam.
  - Power consumption: 2W/cm<sup>2</sup>; Low power mode: 1W/cm<sup>2</sup> (**High power consumption**)
- Simulation results showed that the readout size can be optimized at 500μm×500μm.
  - Number of the readout channels and power consumption need to be optimized.
  - Focused on **100mW/cm<sup>2</sup> and 500μm readout** for CEPC ref-TDR (2-phase CO<sub>2</sub> cooling **OK!**)

	PASA+ALTRO	Super-ALTRO	SAMPA	WASA_v1
TPC	ALICE	ILC	ALICE upgrade	CEPC
Pad Size	4x7.5 mm <sup>2</sup>	1x6 mm <sup>2</sup>	4x7.5 mm <sup>2</sup>	1x6 mm <sup>2</sup>
No. of Channels	5.7 × 10 <sup>5</sup>	1-2 × 10 <sup>6</sup>	5.7 × 10 <sup>5</sup>	2 × 10 <sup>6</sup>
Readout Detector	MWPC	GEM/MicroMegas	GEM	GEM/MicroMegas
Gain	12 mV/fC	12-27 mV/fC	20/30 mV/fC	10-40 mV/fC
Shaper	CR-(RC) <sup>4</sup>	CR-(RC) <sup>4</sup>	CR-(RC) <sup>4</sup>	CR-RC
Peaking time	200 ns	30-120 ns	80/160 ns	160-400 ns
ENC	370+14.6 e/pF	520 e	246+36 e/pF	569+14.8 e/pF
Waveform Sampler	Pipeline ADC	Pipeline ADC	SAR ADC	SAR ADC
Sampling Rate	10 MHz	40 MHz	10 MHz	10-100 MHz
Sampling Resolution	10 bit	10 bit	10 bit	10 bit
Power: AFE	11.7 mW/ch	10.3 mW/ch	9 mW/ch	1.4 mW/ch
Power: ADC	12.5 mW/ch	33 mW/ch	1.5 mW/ch	0.8 mW/ch@40 MHz
Power: Digital Logics	7.5 mW/ch	4.0 mW/ch	6.5 mW/ch	2.7 mW/ch@40 MHz
<b>Total Power</b>	<b>31.7 mW/ch@10MHz</b>	<b>47.3 mW/ch@40 MHz</b>	<b>17 mW/ch@10 MHz</b>	<b>4.9 mW/ch@40 MHz</b>
CMOS Process	250 nm	130 nm	130 nm	65 nm



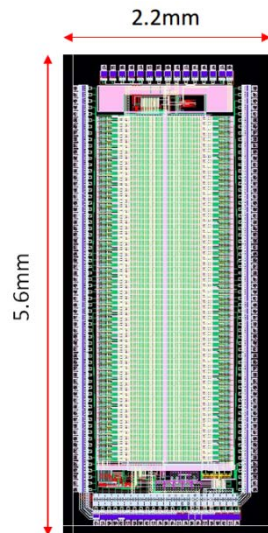
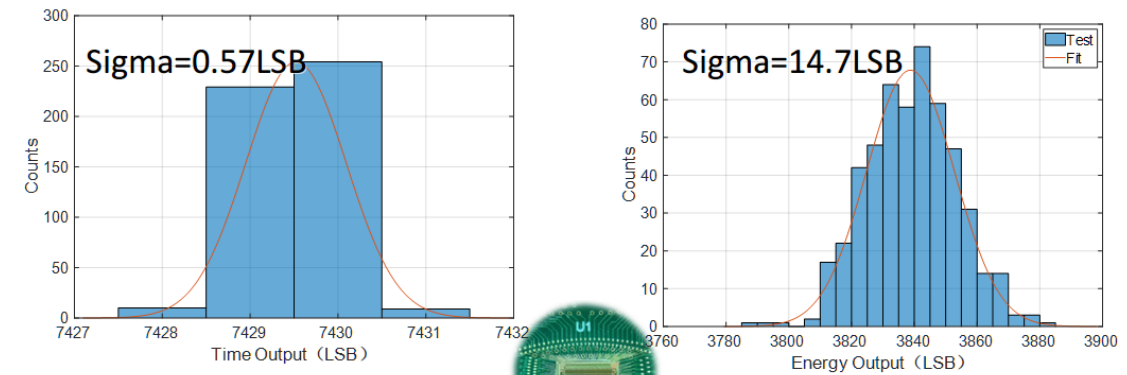
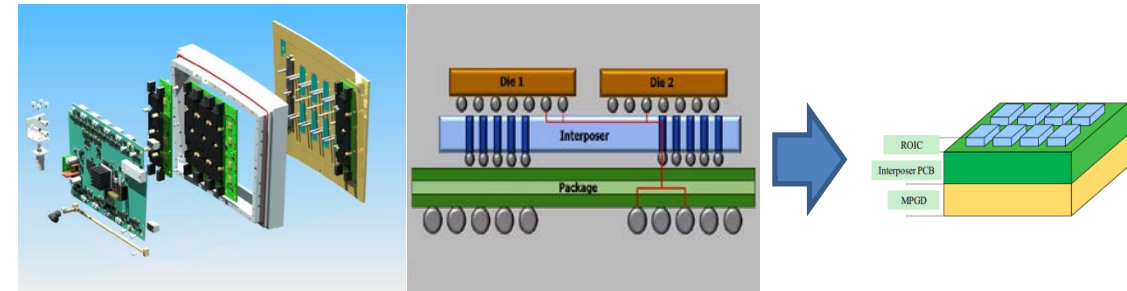
# Detailed design of electronics and BEC

## ■ Pixelated Readout Electronics: TEPix development

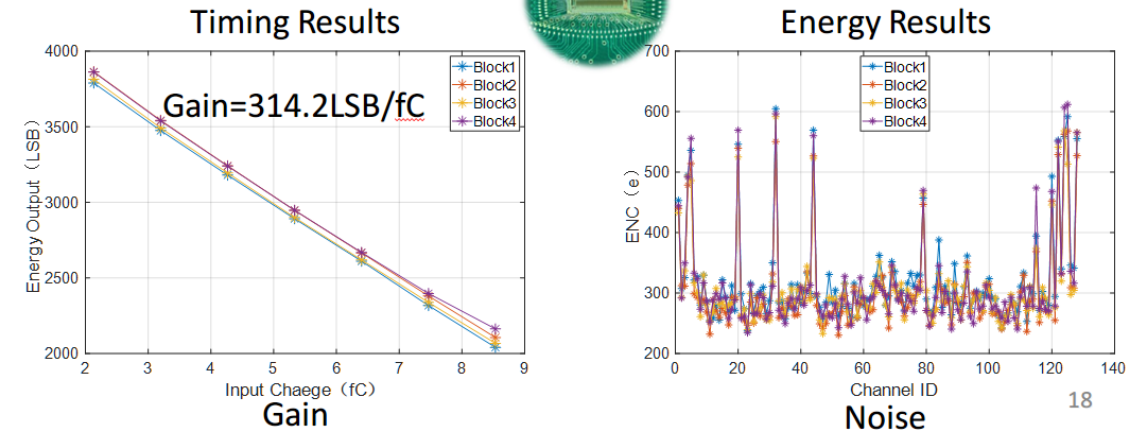
- Multi-ROIC chips + Interposer PCB as RDL
- Four-side bootable

## ■ TEPix: Low power Energy/Timing measurement

- Low power consumption: 0.5mW/ch@2<sup>nd</sup> Chip
- Timing: 1 LSB(<10ns)
- Noise: 300e- (high gain)

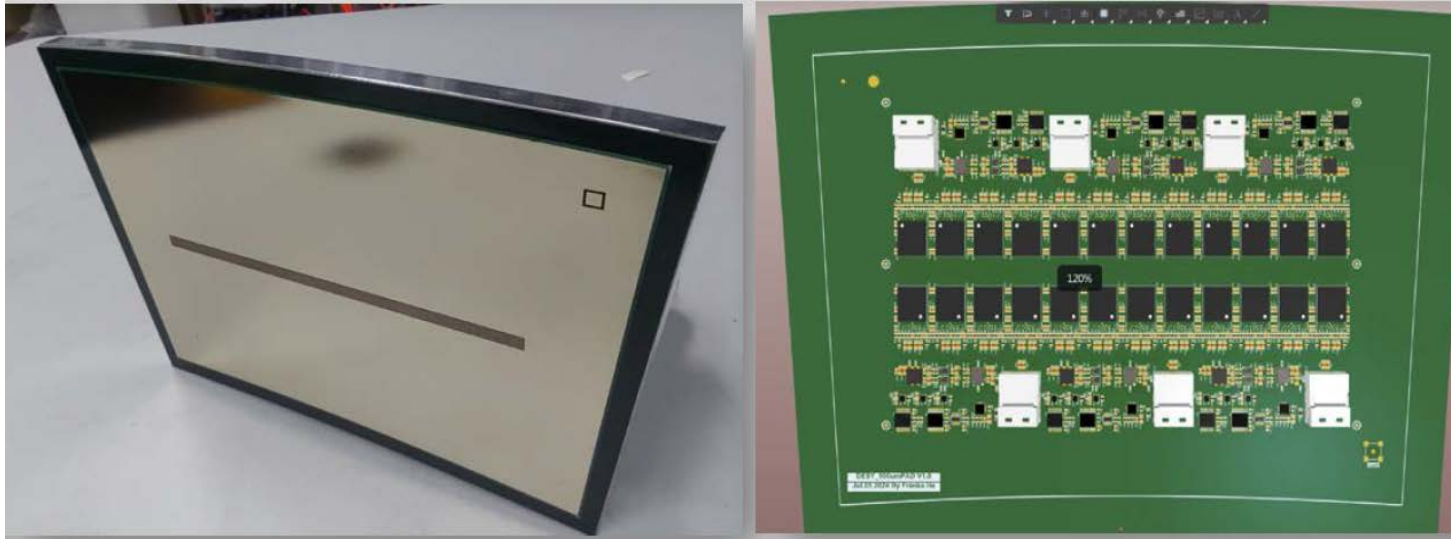
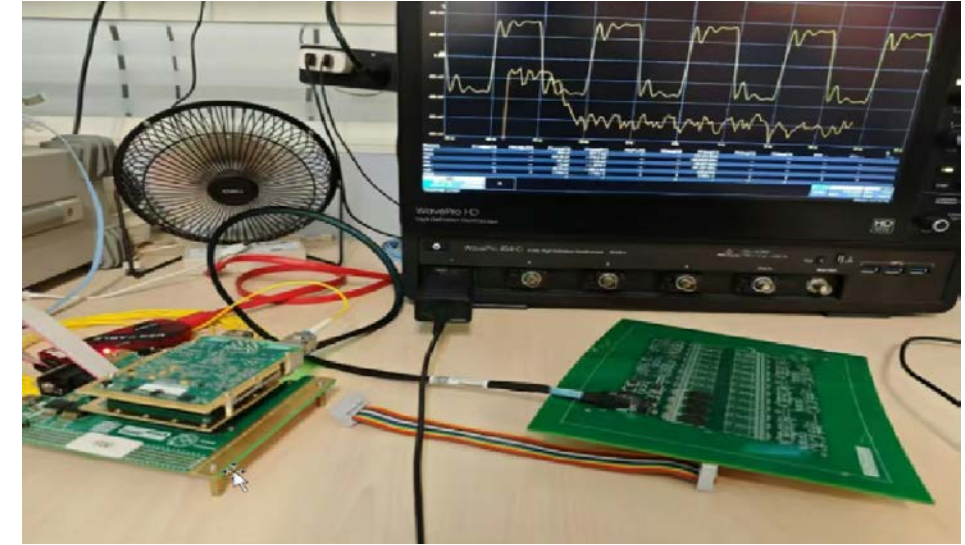


Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns

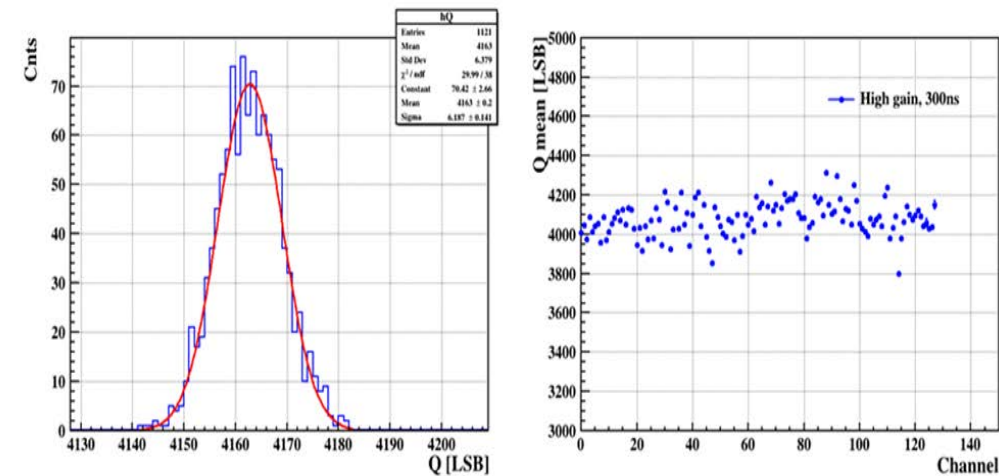


# Validation and commissioning of TPC prototype

- R&D on Pixelated TPC readout for CEPC TDR.
  - ASIC chip developed and **2<sup>nd</sup> prototype wafer has been done** and tested.
  - The TOA and TOT can be selected as the initiation function in the ASIC chip
- Beam test of the pixelated readout TPC prototype in preparation. (**February and April, 2025**)



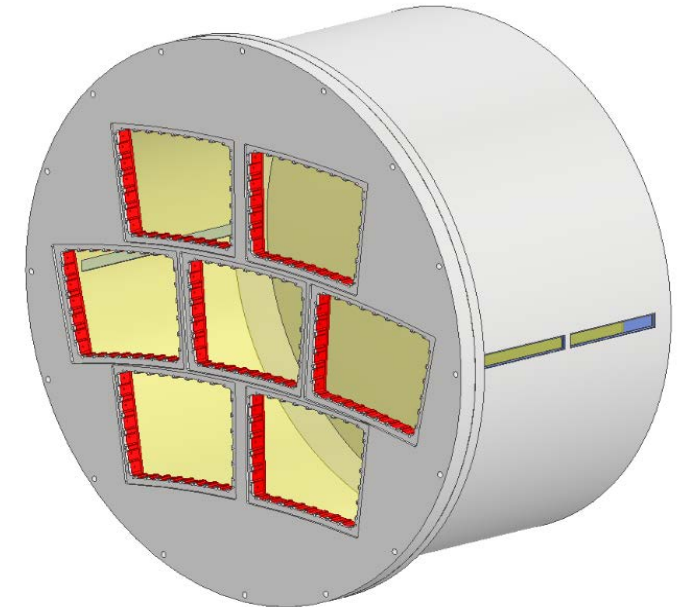
Photos TPC modules assembled for the beam test



Amplitude (left) and Uniformity/ch (right)<sup>21</sup>

# Work plan

- Short term work plan (**before June, 2025**)
  - Optimization of TPC detector for CEPC ref-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 pixelated 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.



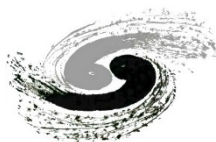
Milestones achieved	Before June, 2025	Beyond TDR
Ion backflow suppression	$IBF \times Gain < 1$ (Gain=2000)	Graphene technology
Pixelated readout prototype	Validation with beam test	Prototype with Multi-modules
Power consumption ASIC	$\sim 100 \text{ mW/cm}^2$ (60nm ASIC)	Optimization $330 \mu\text{m} - 500 \mu\text{m}$
PID resolution	3% (dN/dx)	<3% (dN/dx)
Material budget (barrel)	Carbon Fiber	Full size prototype

# Summary

- TPC detector prototype R&D using pad readout towards pixelated readout for Higgs and calibration Z pole at 3.0Tesla run at the future  $e^+e^-$  collider.
- Pixelated TPC is chosen as the baseline gaseous tracker in CEPC ref-TDR. The simulation results show that both of PID performance and the momentum resolution are good. Validation with TPC prototype in preparation before TDR.
- Synergies with CEPC/FCCee/EIC/LCTPC allow us to continue R&D and ongoing with the significant international collaboration. **All of contributions will input to CEPC ref-TDR in next few months.**



# Thank you for your attention!



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