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High Spatial Resolution Time Projection Chamber Technology R&D for Future e+e- Collider

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and some inputs from LCTPC international collaboration

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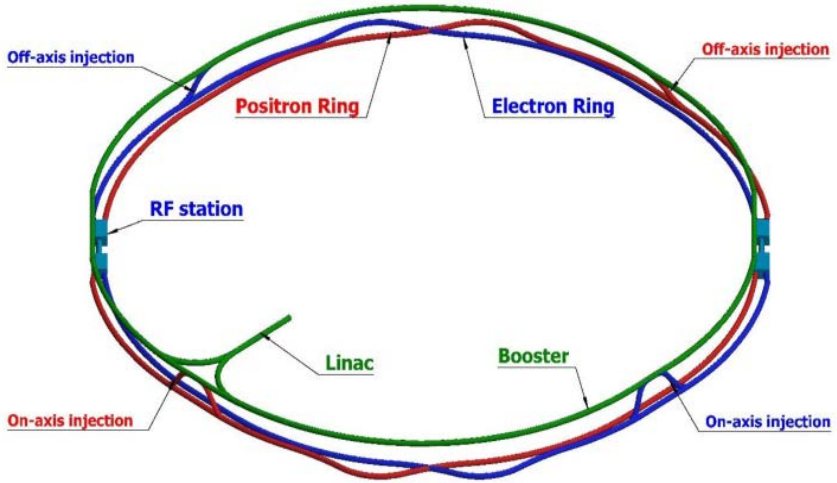
Content

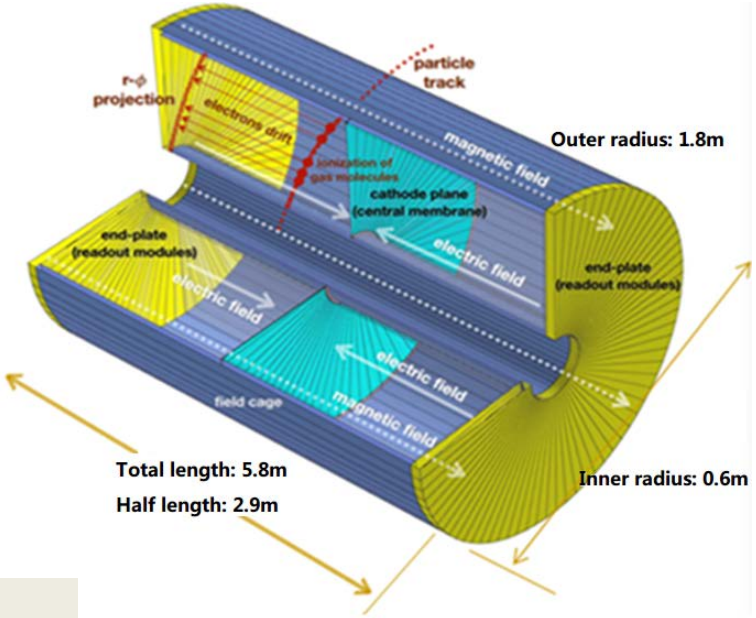
- **Motivation and physics requirements**
- **High spatial resolution TPC R&D**
- **Updated pixelated readout TPC R&D**
- **Summary**

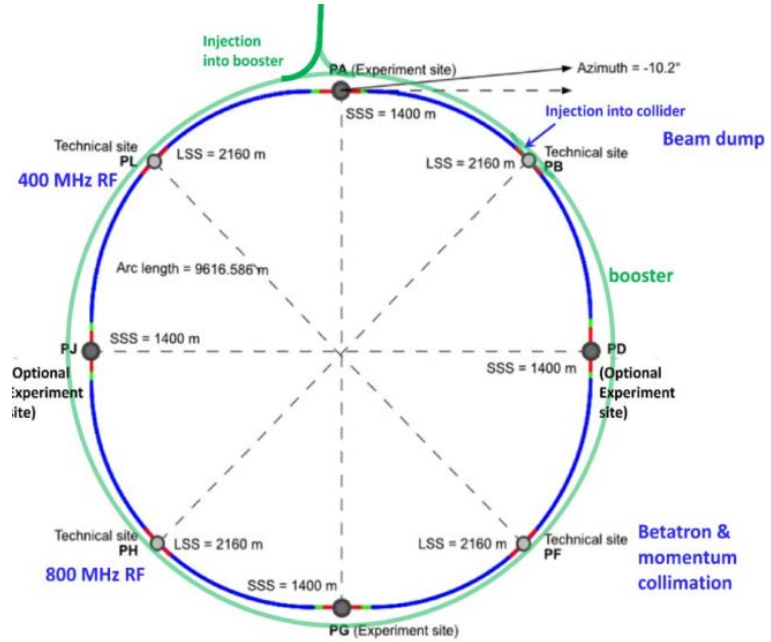
- **Motivation and physics requirements**

Motivation and physics requirements 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 is a promised candidate as the main track detector in CEPC TDR
- TPC technology can be of interest for other future colliders (EIC, FCC-ee, KEKb…)
- Pixelated readout TPC is potential to **improve PID requirements of Flavor Physics** at e+e- collider.







Circular Electron Positron Collider (CEPC)

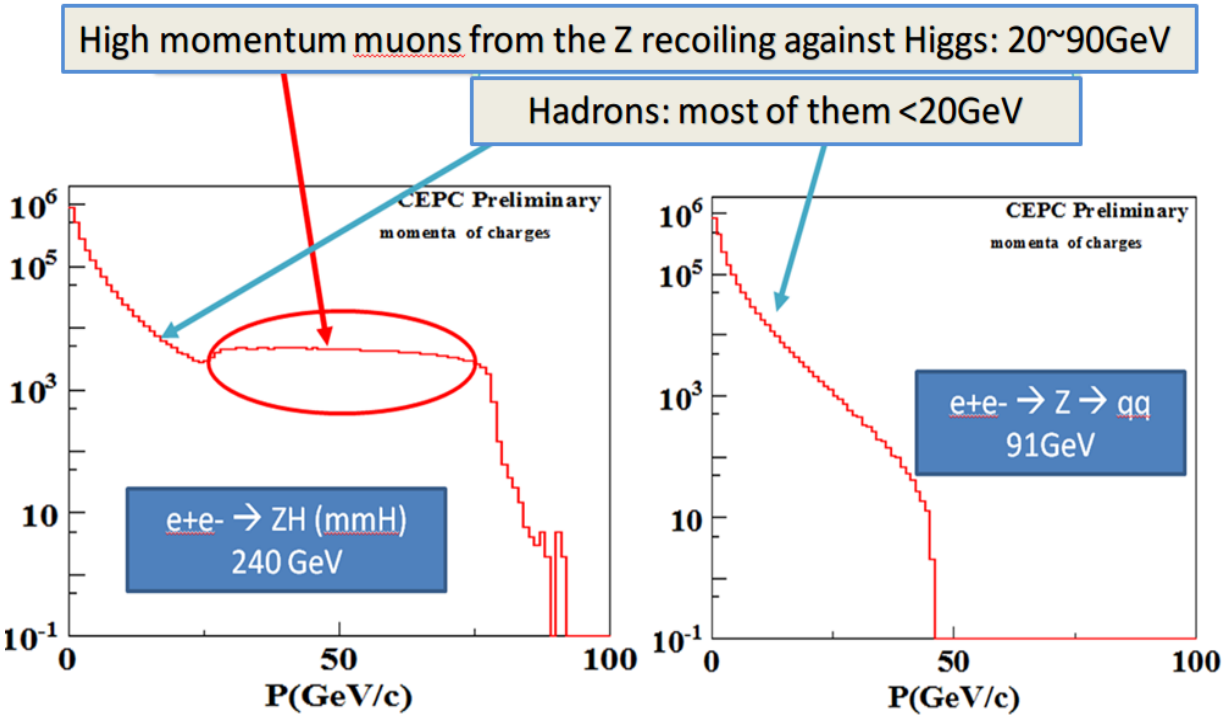
Future Circular Collider (FCCee)

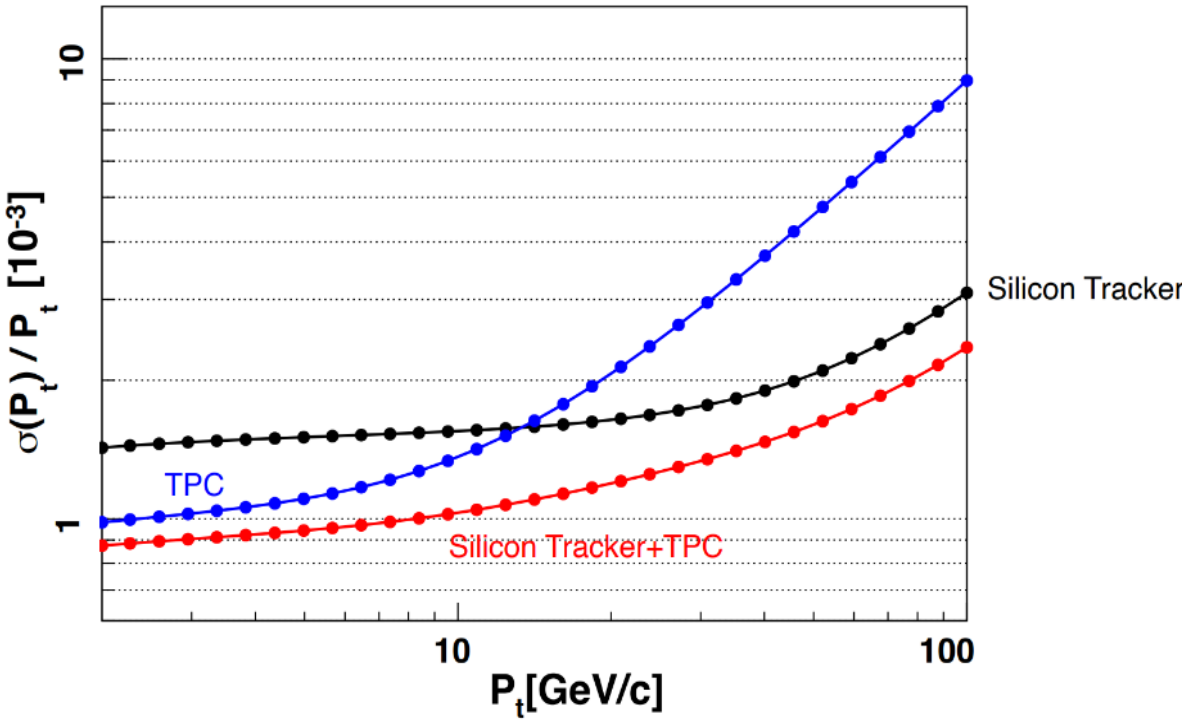
https://arxiv.org/abs/1811.10545

https://arxiv.org/abs/2203.08310

Physics requirements on future circular e+e- collider

- Operation stages in CEPC TDR: **10-years Higgs → 2-years Z pole → 1-year W**
- Physics Requirements of tracker
  - Thousands of hits with high spatial resolution compatible with PFA algorithm (low X_0)
  - Beneficial for the lower momentum resolution
  - PID of charged hadrons improvement to flavor physics and jet substructure





https://doi.org/10.1140/epjc/s10052-018-5876-z

- **High spatial resolution TPC R&D**

Main Technical Challenges

- **Pixelated readout TPC (Baseline)**

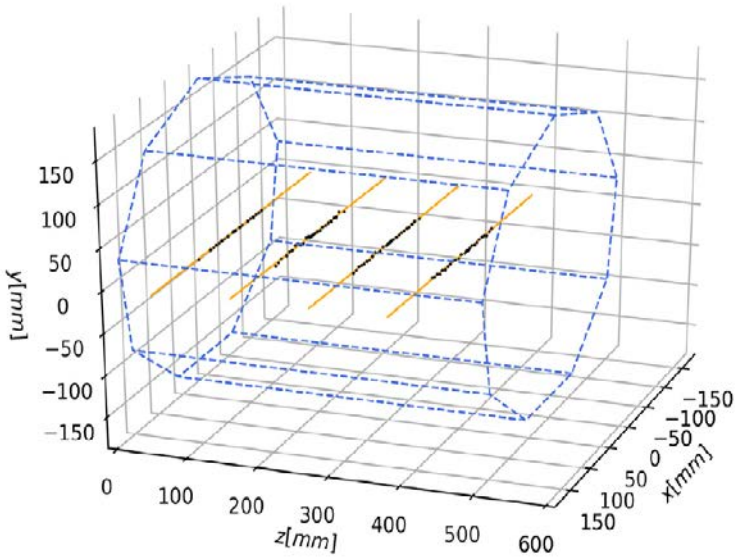
Critical key issues

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

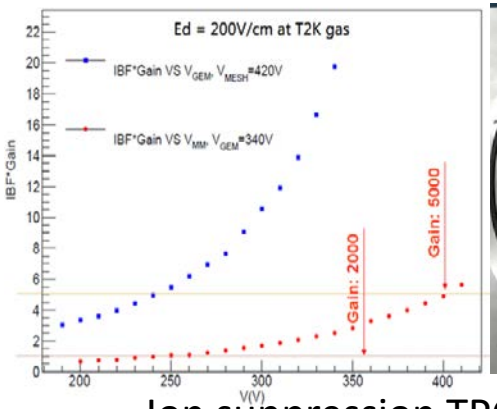
Roadmap of CEPC TPC detector R&D

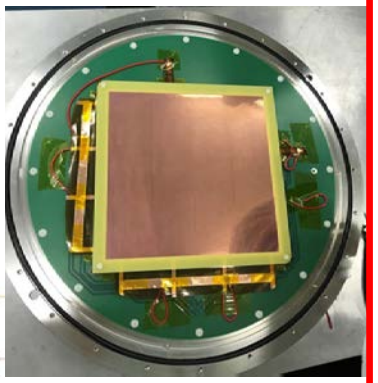
- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to **TPC prototype R&D for Higgs and Tera-Z**
  - Easy-to-install modular design of Pixelated readout TPC for CEPC TDR
- **Achievement by far:**
  - **IBF×Gain ~1 @ G=2000** validation with hybrid TPC module
  - Spatial resolution of **$\sigma_{r\varphi}$≤100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

TPC prototype with integrated 266nm UV laser

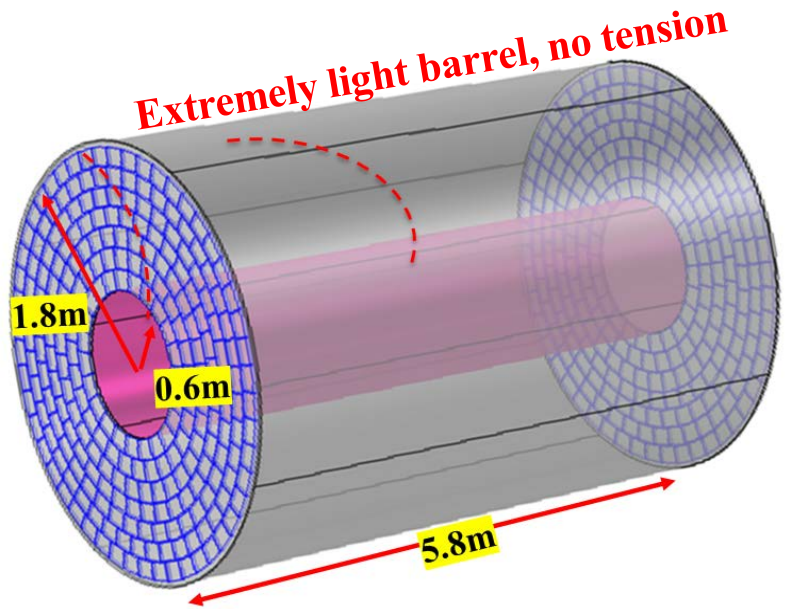


Achievement





Ion suppression TPC module R&D

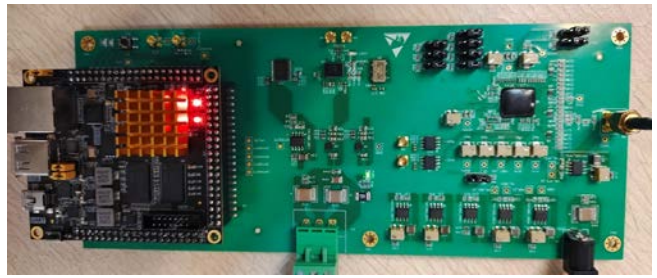


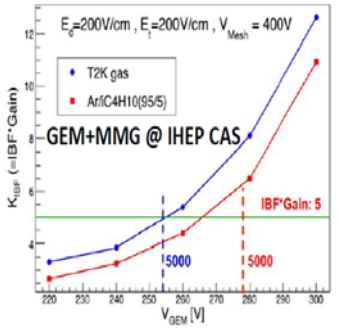
Geometry of TPC for CEPC TDR

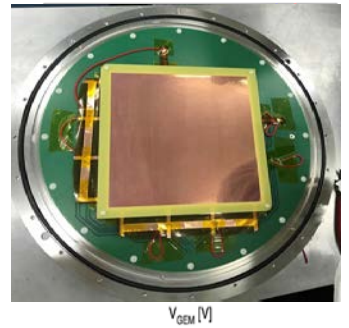
https://doi.org/10.1016/j.nima.2022.167241

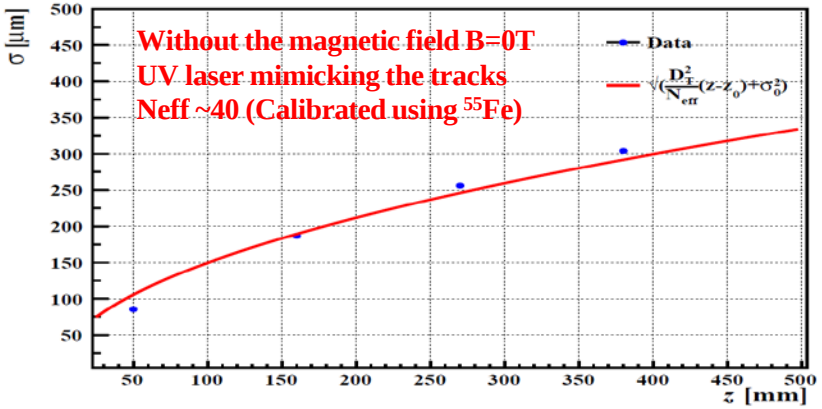
Highlights of TPC prototype integrated with 266nm UV laser tracks

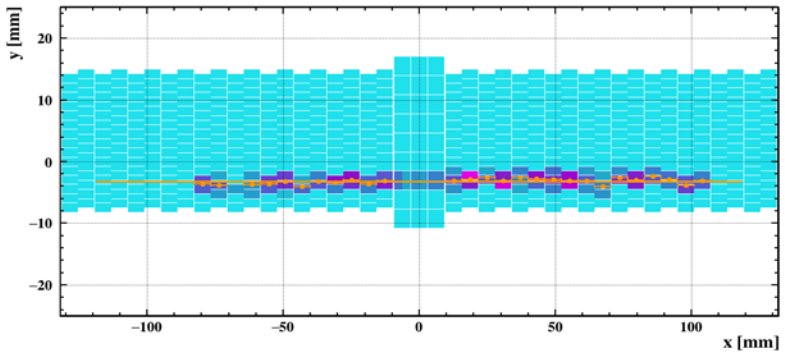
- **Highlights of CEPC TPC R&D and toward reasonable pixelated readout TPC**
  - Massive production and assemble MPGD lab has been setup at IHEP
  - TPC prototype integrated 266nm UV laser tracks has been studied and analyzed the UV laser signal, all are pretty good to Higgs run.
  - Track reconstruction and the spatial resolution of Pad readout TPC prototype are analyzed.

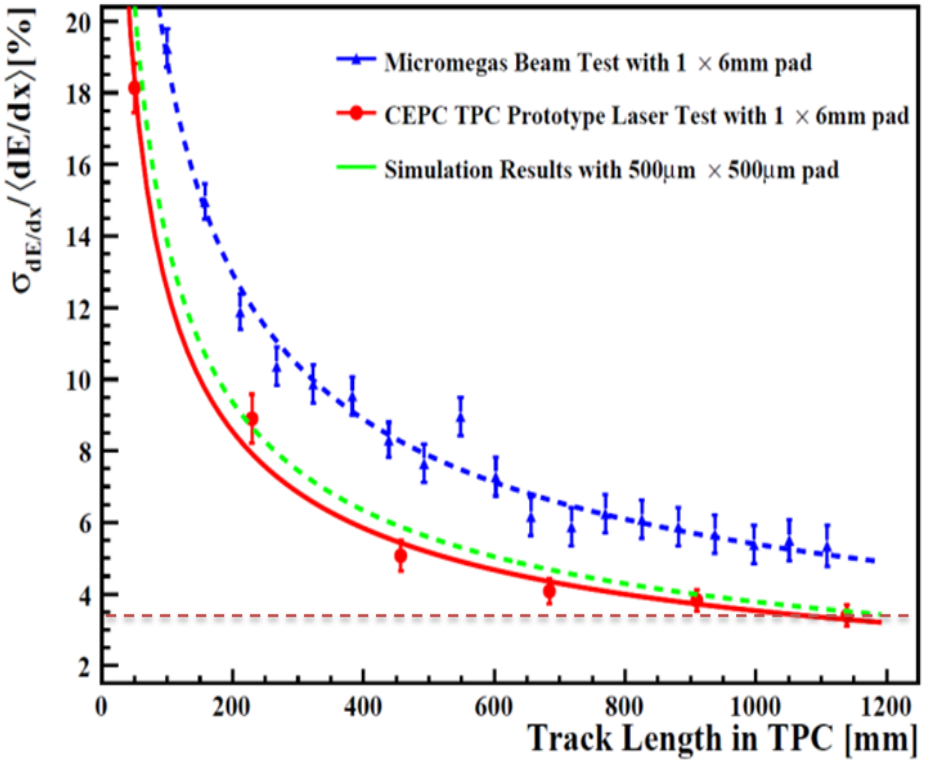












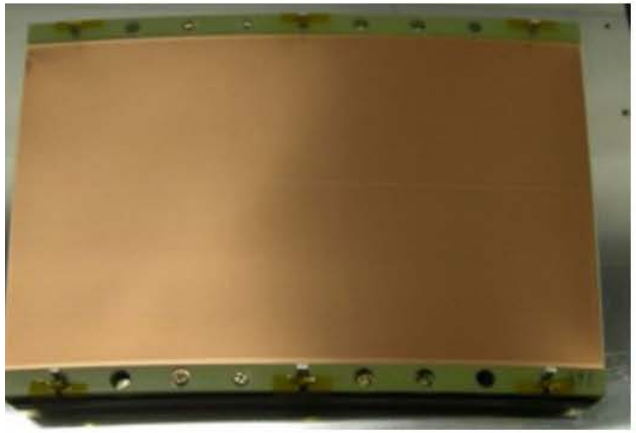
Publications by CEPC TPC group in 2018-2024:

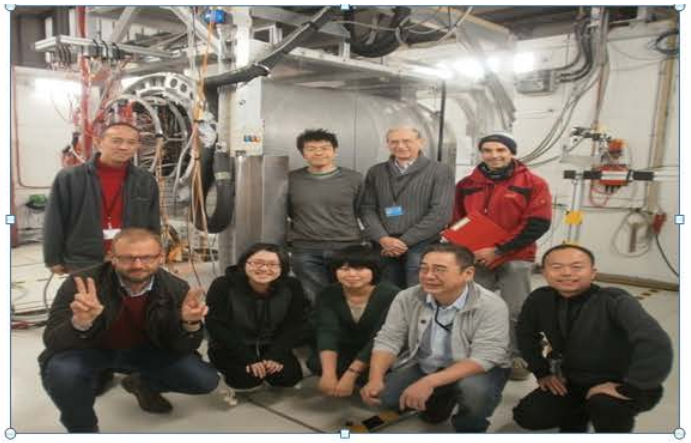
- https://doi.org/10.1088/1748-0221/18/08/E08002
- https://doi.org/10.22323/1.449.0553
- https://doi.org/10.1016/j.nima.2022.167241
- https://doi.org/10.1109/NSS/MIC44867.2021.9875566
- https://doi.org/10.1109/NSS/MIC44845.2022.10399097
- https://doi.org/10.1088/1748-0221/15/09/C09065
- https://doi.org/10.1088/1748-0221/15/05/P05005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

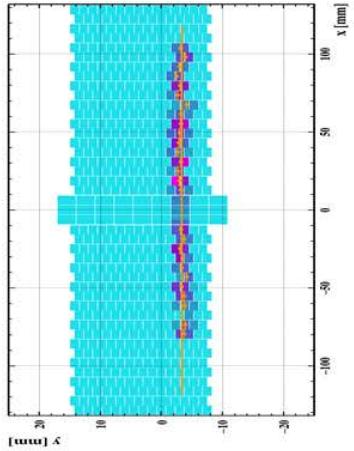
Activity international collaboration

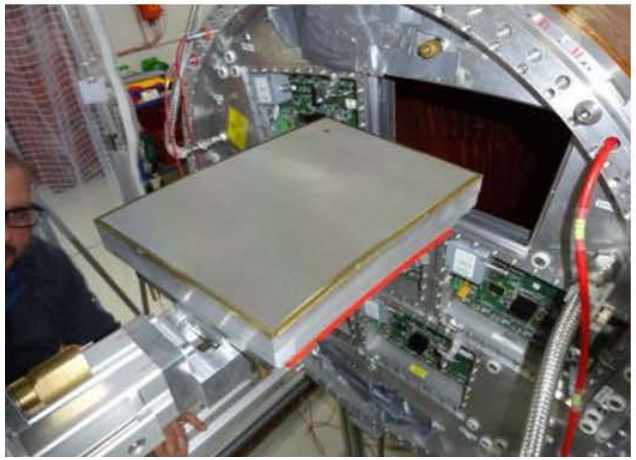
- **Activity collaboration: Pixelated readout and Pad readout from IHEP and LCTPC collaboration**
  - Large Prototype setup have been built to compare different detector readouts for Tera-Z
  - PCMAG: B < 1.0T, bore Ø: 85cm, Spatial resolution of $\sigma r\phi \leq 100$ μm
  - Collaboration implement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

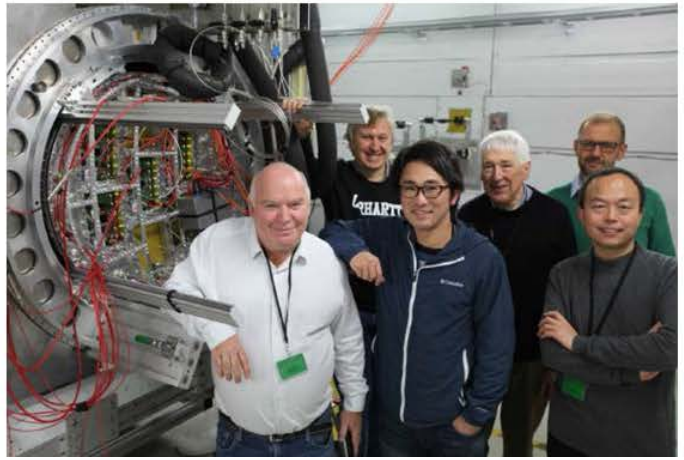
ArXiv. (2023)2006.08562
NIM A (2022) 167241
ArXiv (2022)2006.085
JINST 16 (2021) P10023
JINST 5 (2010) P10011
NIM A608 (2009) 390-396

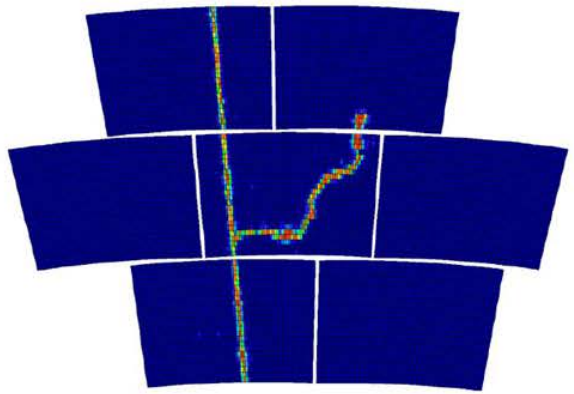






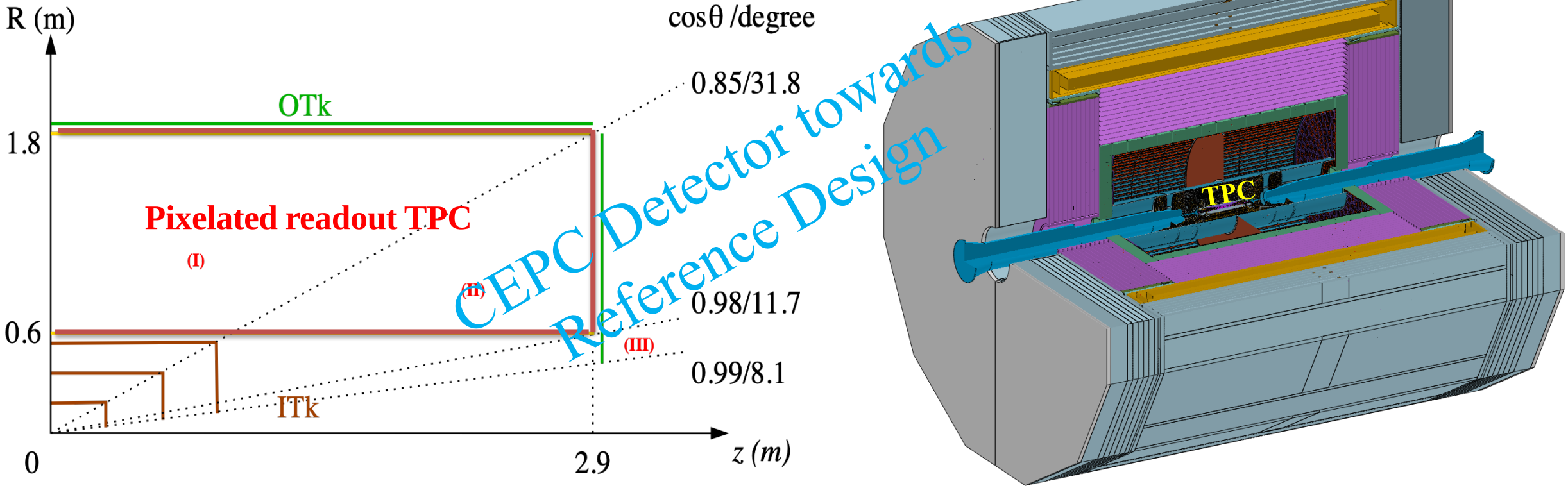






Track detector system in CEPC Phy.&Det. TDR

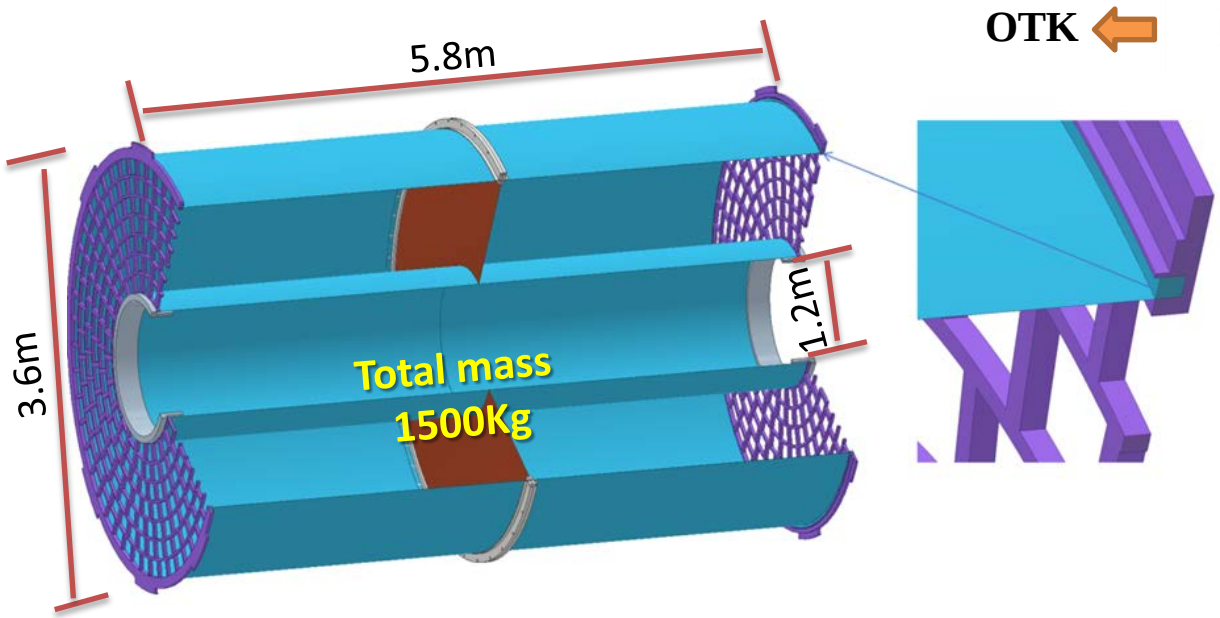
- Tracker detector system: Silicon combined with gaseous chamber as the tracker and PID
  - Pixelated readout TPC as the **baseline technology** in CEPC ref-TDR.
    - Radius of TPC from 0.6m to 1.8m
  - DC as an **alternative** option at Tera-Z.

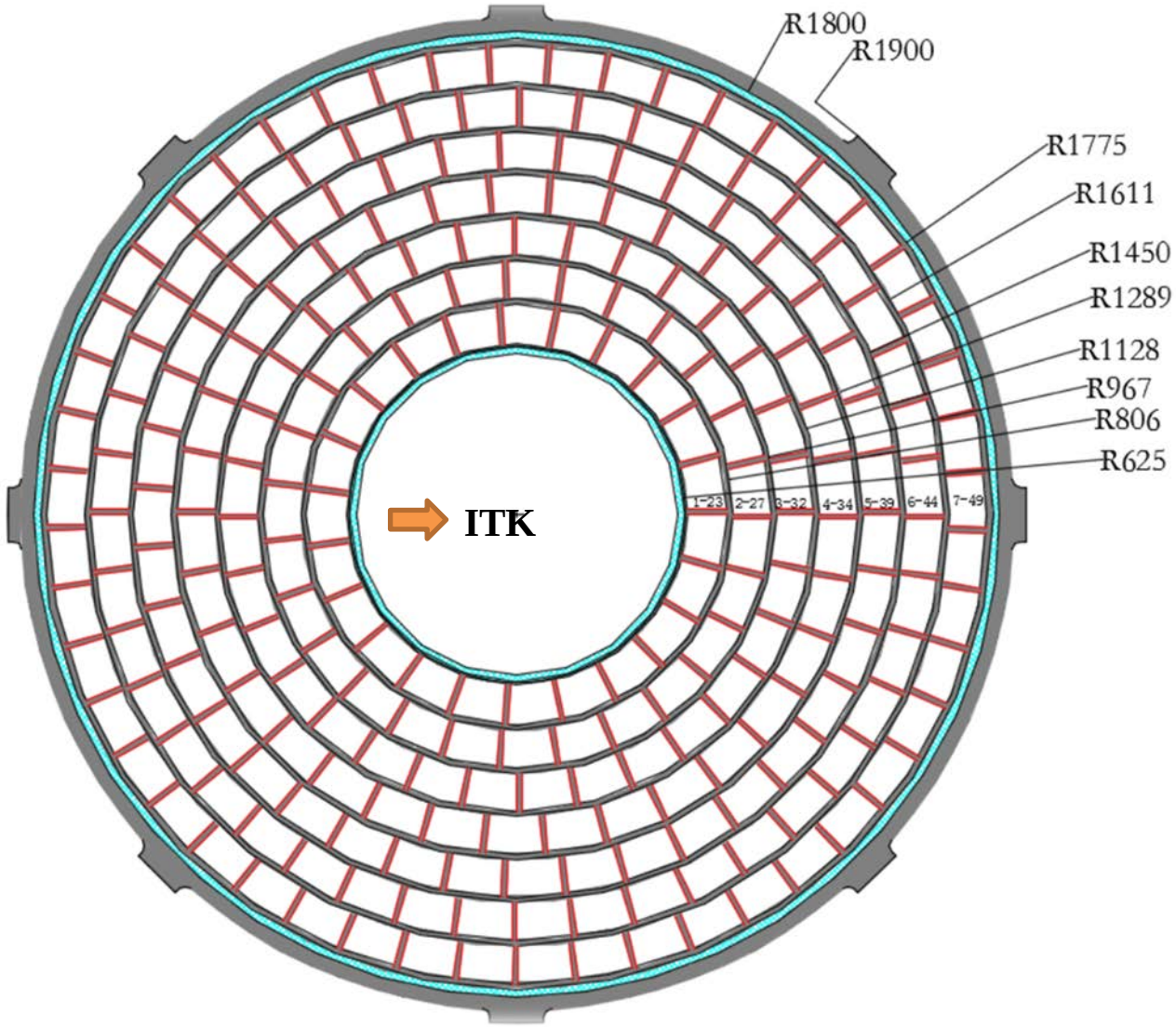


Geometry of the track detector system in CEPC TDR

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
Operation gases	T2K: Ar/CF4/iC4H10=95/3/2
Maximum drift time	34μs @ 2.75m
Detector modules	Pixelated Micromegas

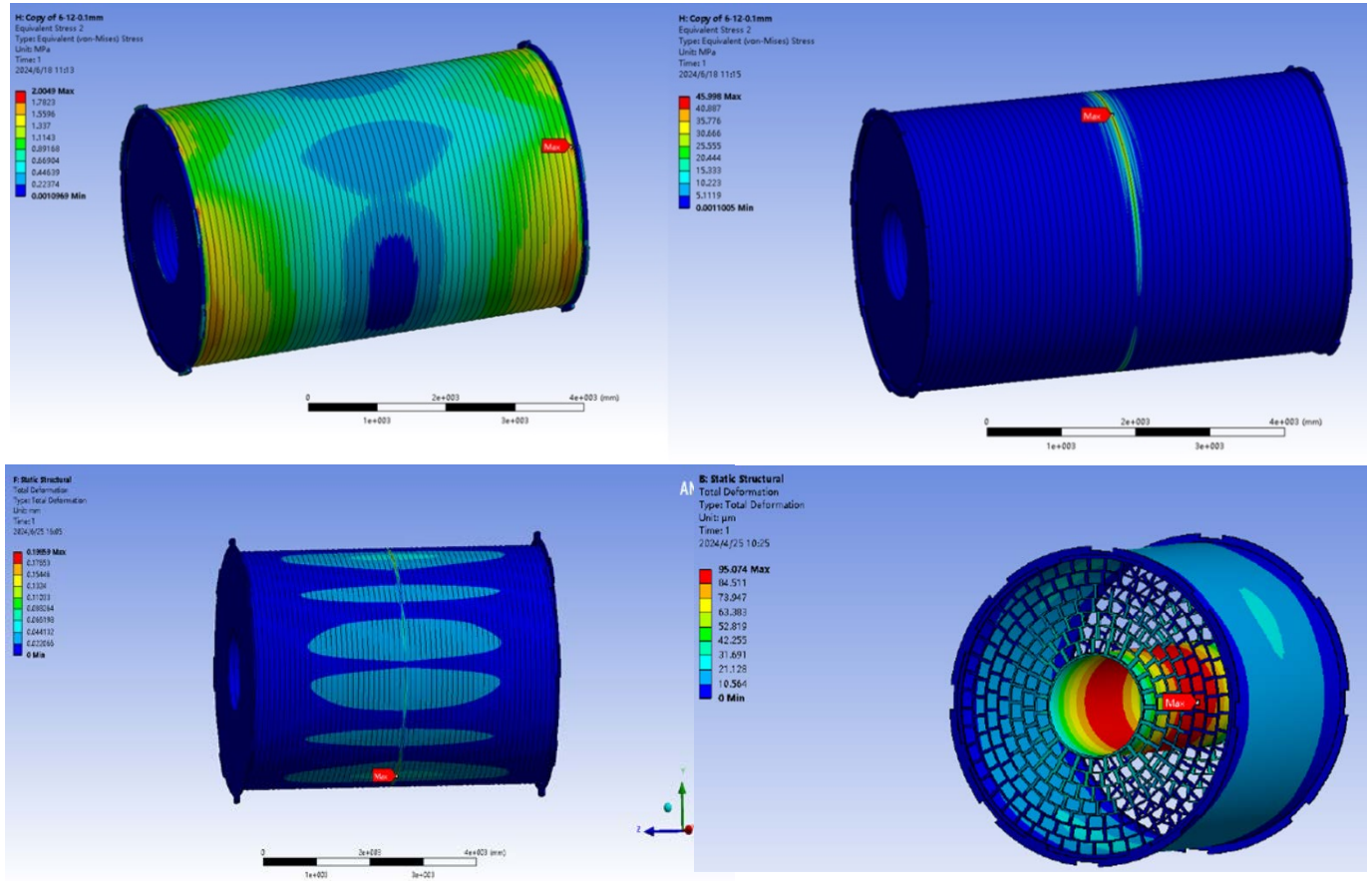




Detailed design of TPC detector in ref-TDR

Ultra-light barrel and FEA analysis

- Consideration of new 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**

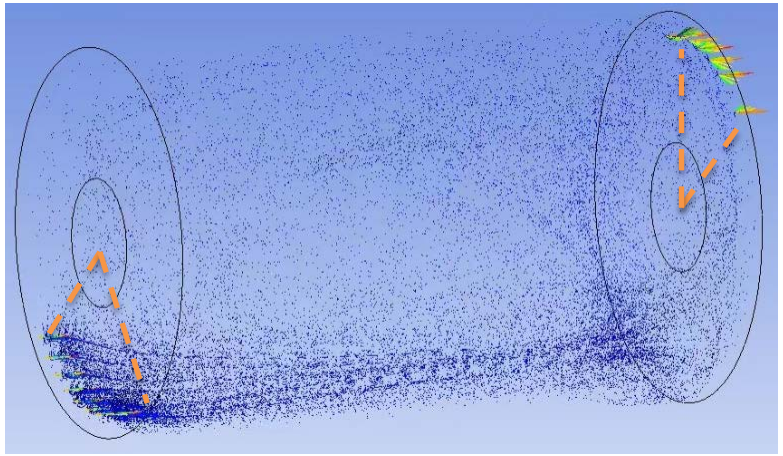
- **Low material of the TPC endcap**

15%X_0 in total, including

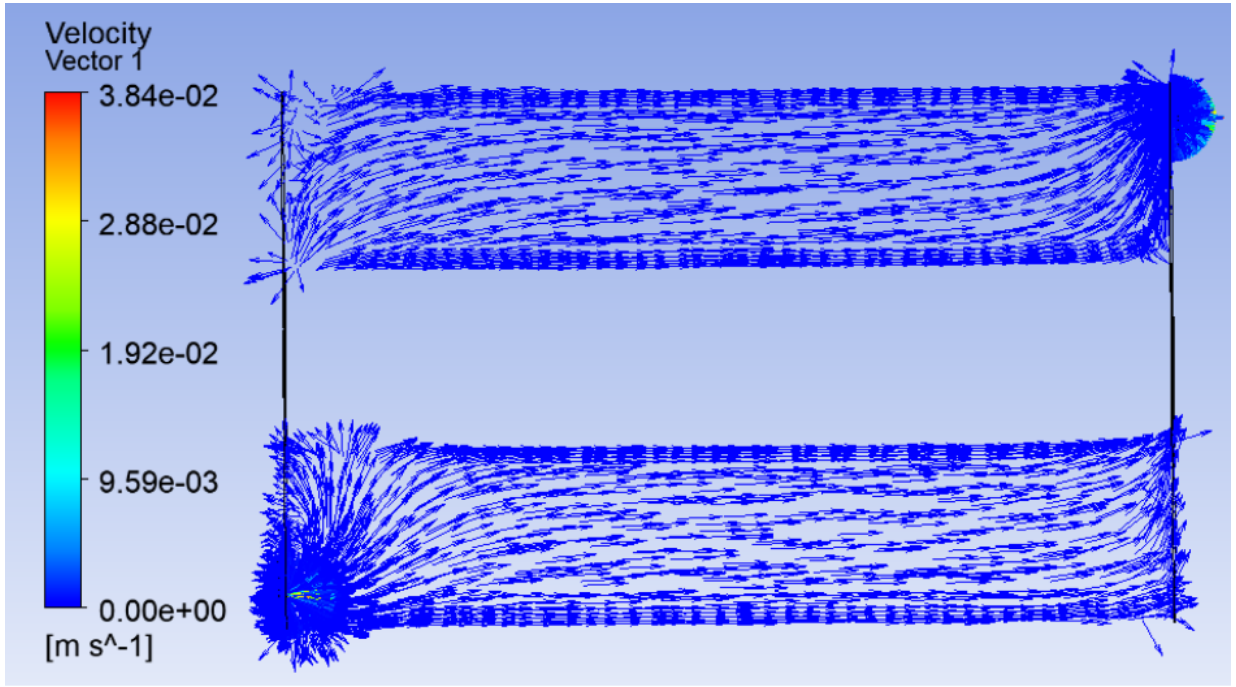
Readout plane, front-end-electronics	4%
Cooling	2%
Power cables	9%

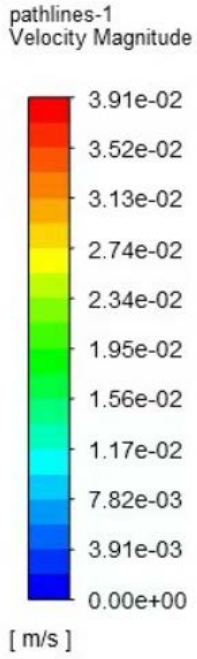
Optimization of Gas flow in Chamber

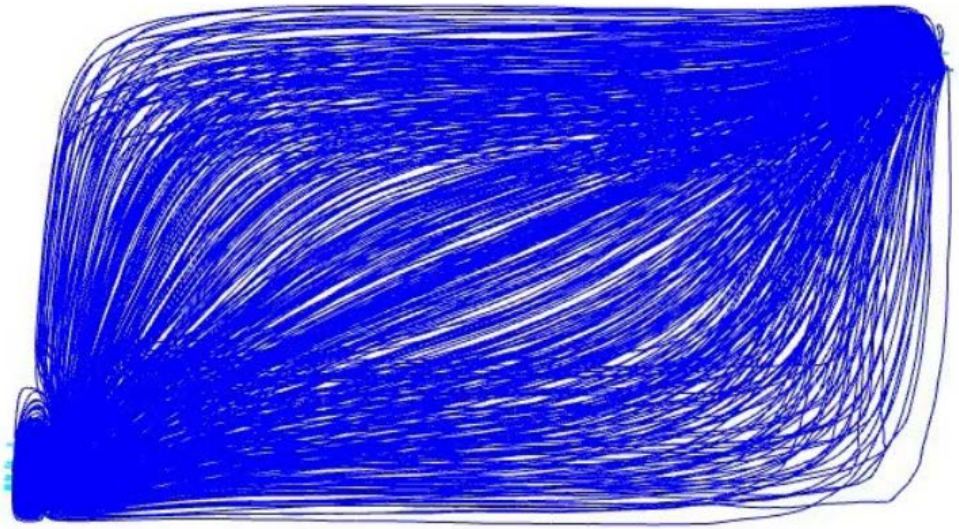
- Requirement: Gas uniformity of **99% or more** in large TPC chamber
  - **8 Ø10mm** gas inlets + **8 Ø10mm** gas outlets (opposite, 90°/endcap)
  - Working Gas Flow: 0.3 – 0.5 L/min
  - **Online monitoring system**: O_2 (ppm) and H_2O (ppm)
  - Friendly the gases recycle system also considered



Optimized inlet and outlet in Chamber





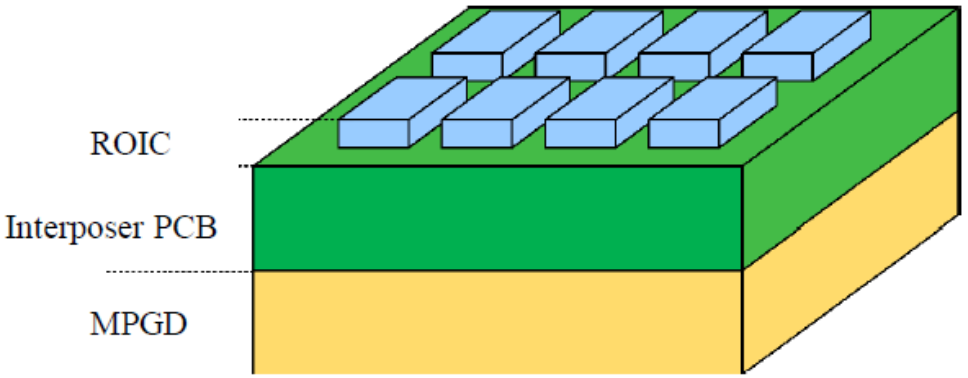


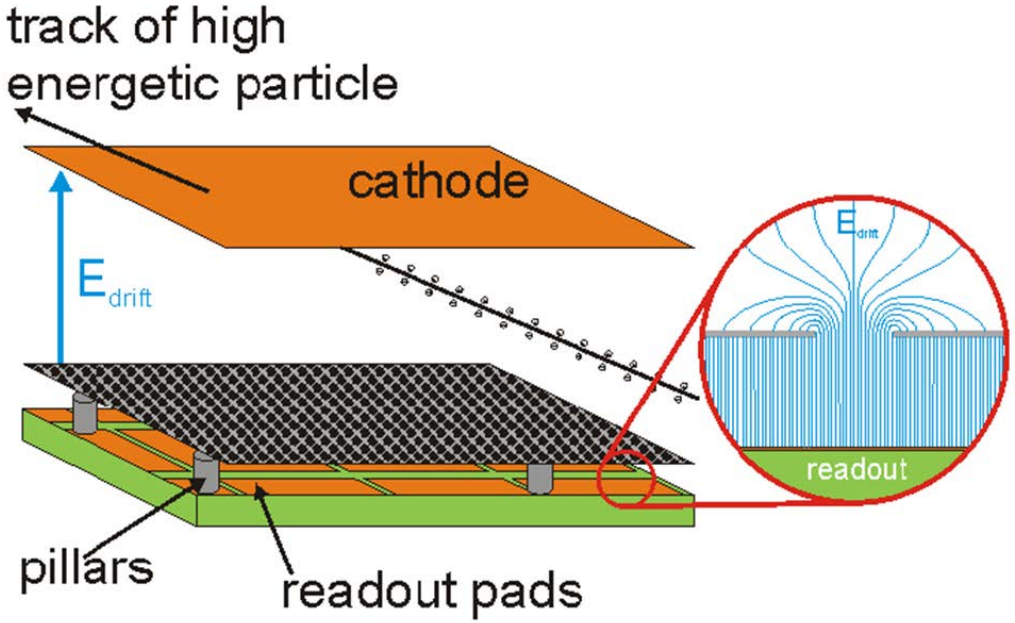
Simulation of gas flow and uniformity distribution in TPC Chamber

- **Updated pixelated readout TPC R&D**

Pixelated readout TPC technology for CEPC TDR

- A pixelated readout TPC is **a good option to provide realistic physics requirements** of Higgs Physical and Tera-Z Physics also (2E36) at CEPC.
  - Pixelated readout→ better resolution → low gain → less distortion
- **Highlights** of Pixelated readout TPC technology for CEPC TDR
  - Can deal with high rates (MHz/cm^2)
  - High spatial resolution → better momentum resolution
  - PID: dE/dx + dN/dx (**In space**)
  - Excellent two tracks separation

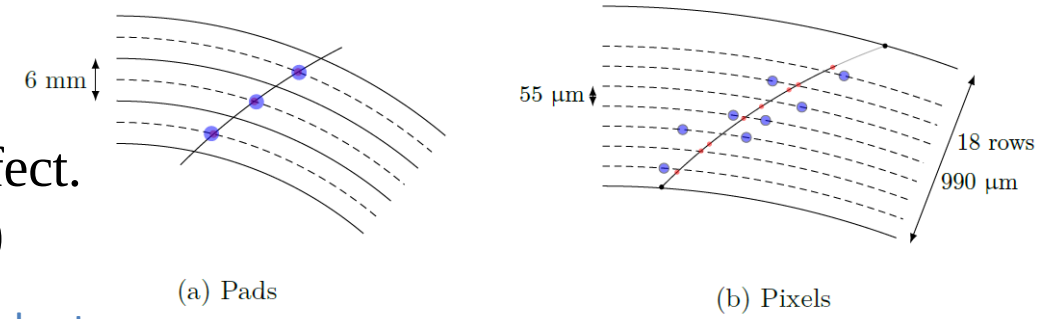




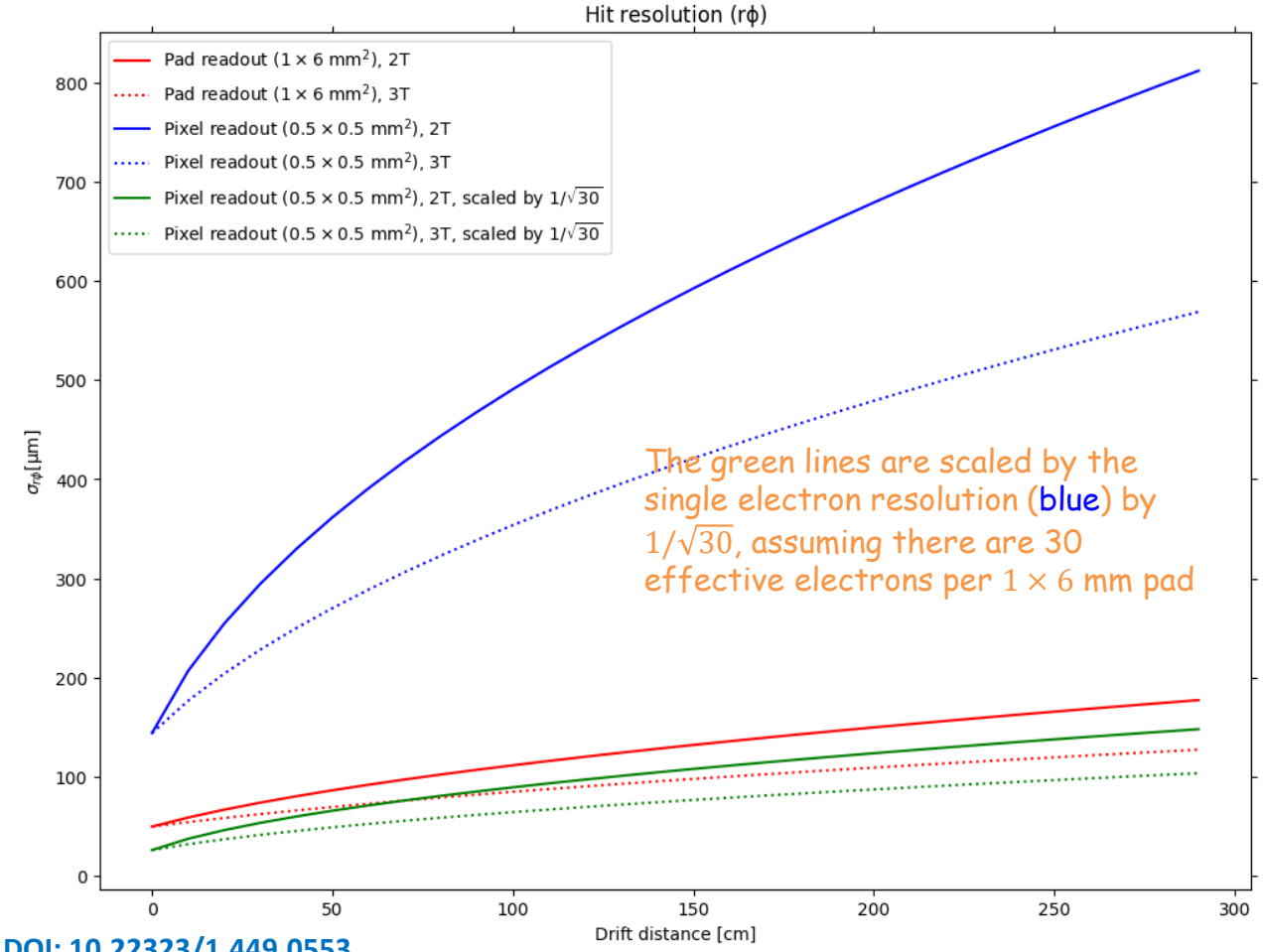
Operation on high luminosity Tera-Z at 2 Tesla

Estimation of the **spatial resolution using pixelated readout**.

- The granularity and the transverse diffusion considered.
- TPC can work well at the 2T B-field **without any E×B** effect.
- Distortion will be considered proportionally at Z (on going)



(a) Pads (b) Pixels



Pad readout:

$$\sigma_{r\phi}^{\text{pad}} = \sqrt{(\sigma_{r\phi 0}^{\text{pad}})^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\text{track}}) + L\frac{D_{r\phi}^2}{N_{\text{eff}}}\sin(\theta_{\text{track}})\left(\frac{6\ \text{mm}}{h_{\text{pad}}}\right)\left(\frac{4.0\ \text{T}}{B}\right)^2}$$

- $\phi_{\text{track}} = 0°, \theta_{\text{track}} = 90°$
- $\sigma_{r\phi 0} = 50\mu\text{m}$
- $N_{eff} = 22$
- $D_{r\phi} = 46.9\mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3\mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

Pixel readout:

$$\sigma_r^{\text{pixel}} = \sigma_{r\phi}^{\text{pixel}} = \sqrt{(\sigma_{r\phi 0}^{\text{pixel}})^2 + LD_{r\phi}^2\left(\frac{4.0\ \text{T}}{B}\right)^2}$$

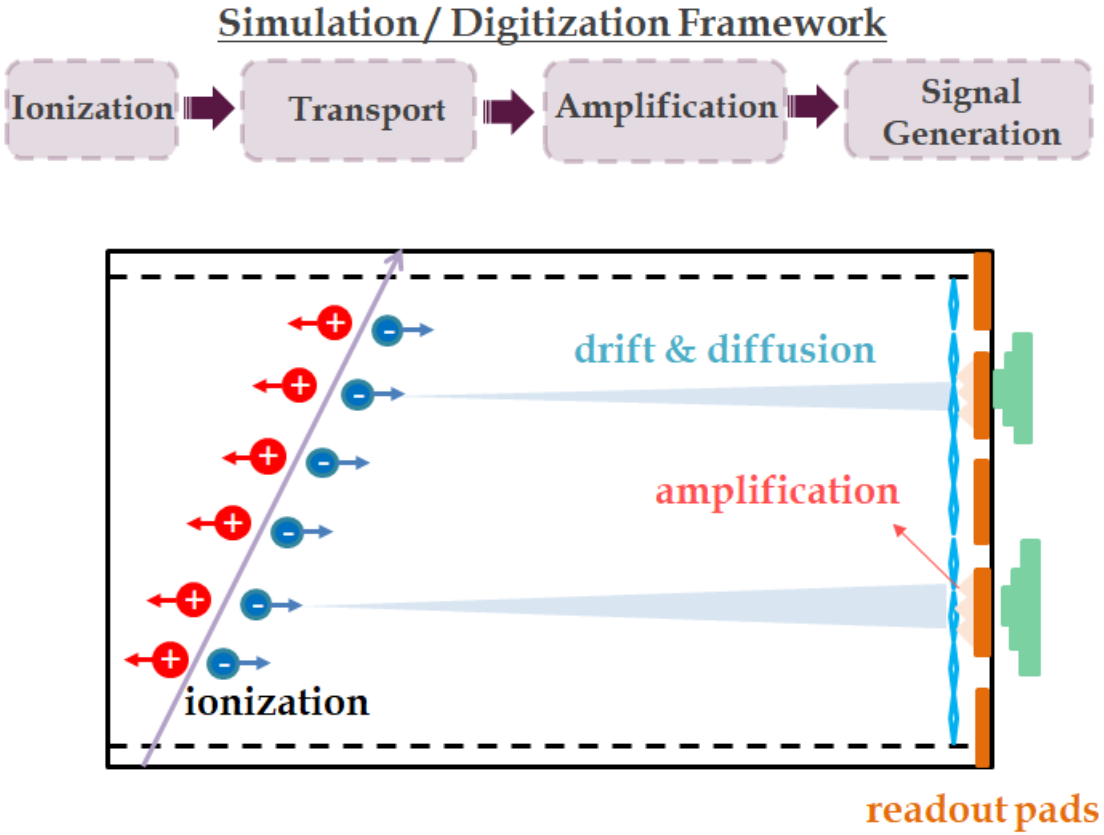
- $\sigma_{r\phi 0} = \frac{500}{\sqrt{12}} = 144\mu\text{m}$
- $D_{r\phi} = 46.9\mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3\mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

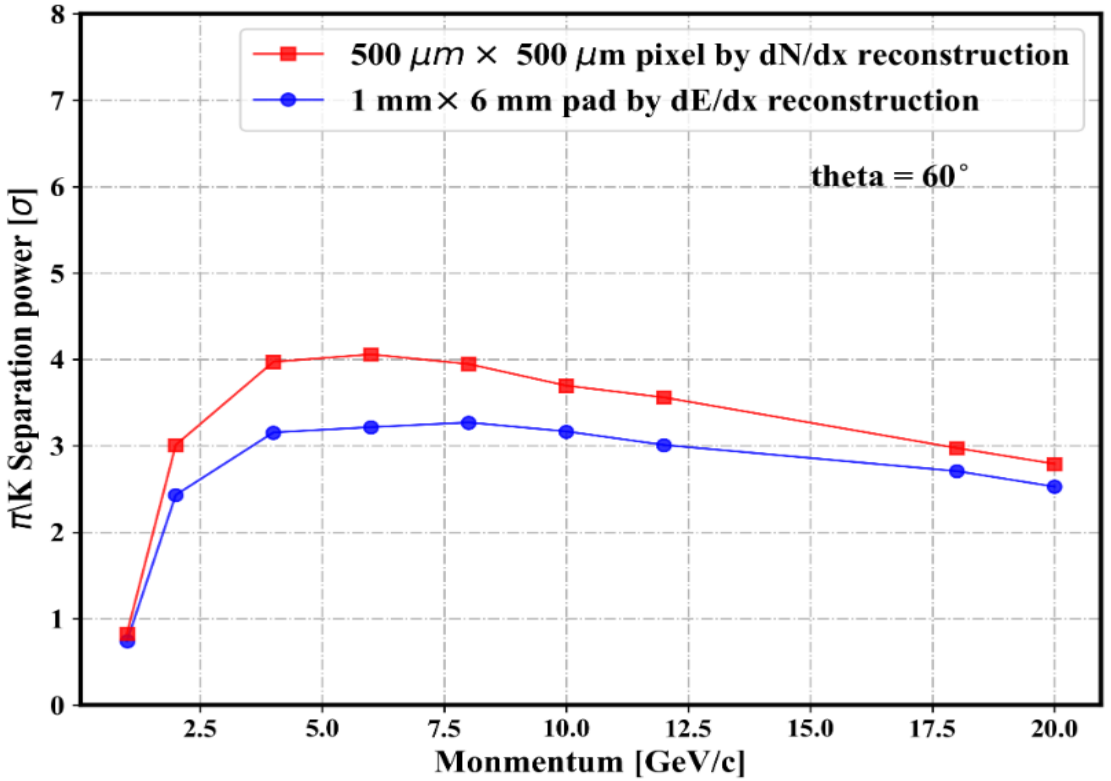
DOI: 10.22323/1.449.0553

Improved dE/dx+dN/dx in space

- 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 has significant improved **PID resolution**

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





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

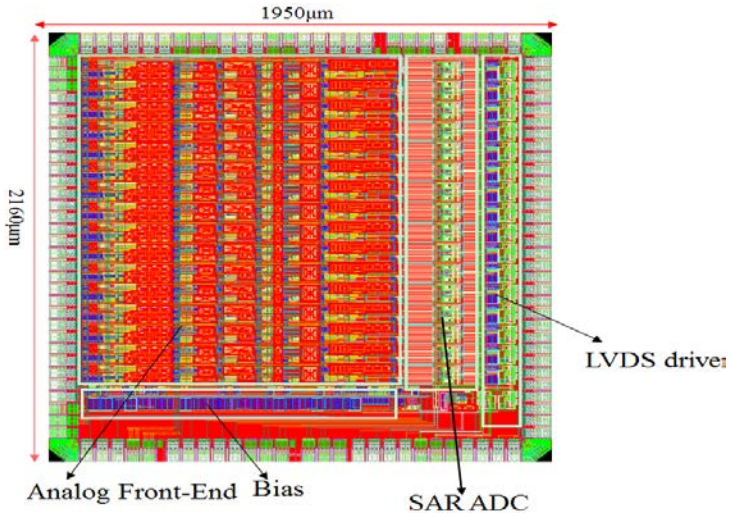
DOI: 10.22323/1.449.0553
EPS-HEP 2023 talk by Yue Chang

Optimization concept option: Pixelated readout TPC @cosθ≃0.98

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 %
$\sigma_{r\varphi}$ (cluster level)	120μm (full drift)	400μm (full drift) w. distortion
σ_z (cluster level)	≃ 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

Reasonable channels and power consumption

- Power consumption relative with the high granularity readout
  - Pad readout TPC@1mm×6mm pad size
    - Total channels: **10^6** ; Total power: **<10 kW** using 2-phase CO_2 cooling
  - Pixelated readout TPC at the endcap
    - Total power: **<10 kW**
      - 2-Phase CO_2 cooling
      - **<100mW/cm^2**
  - ASIC chip and TPC prototyping R&D



	PASA+ALTRO	Super-ALTRO	SAMPA	WASA_v1
TPC	ALICE	ILC	ALICE upgrade	CEPC
Pad Size	4x7.5 mm^2	1x6 mm^2	4x7.5 mm^2	1x6 mm^2
No. of Channels	5.7× 10^5	1-2 × 10^6	5.7 × 10^5	2 x×10^6
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)^4	CR-(RC)^4	CR-(RC)^4	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
Total Power	31.7 mW/ch@10MHz	47.3 mW/ch@40 MHz	17 mW/ch@10 MHz	4.9 mW/ch@40 MHz
CMOS Process	250 nm	130 nm	130 nm	65 nm

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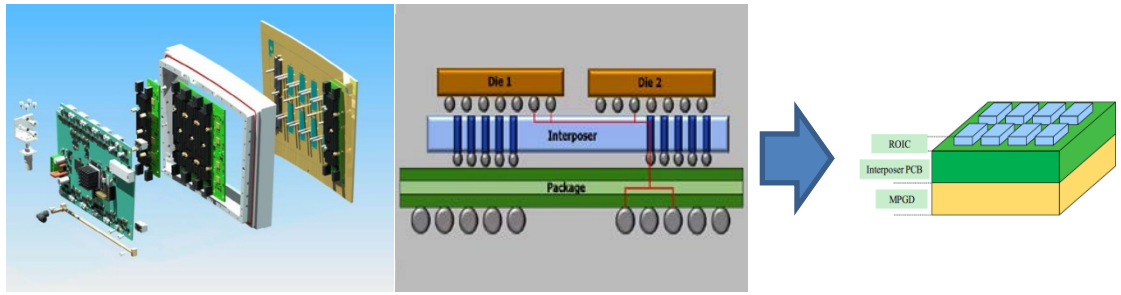
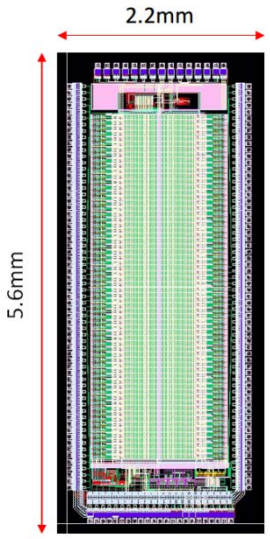
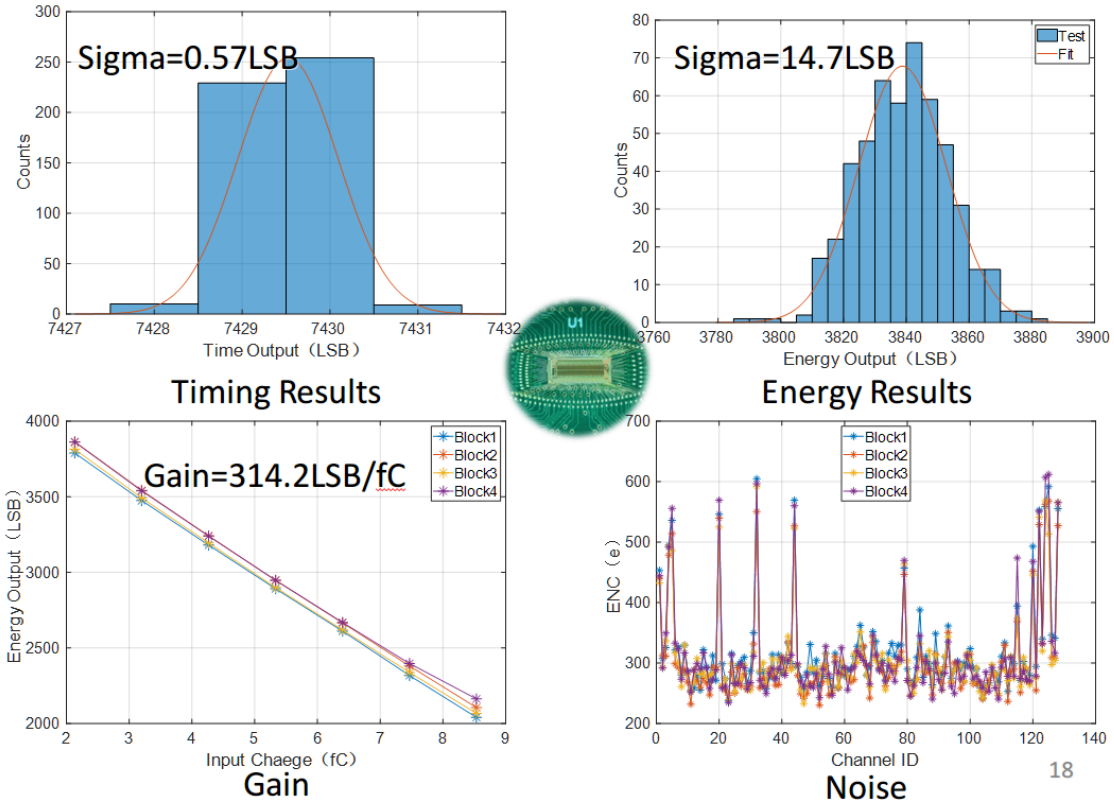
Prototype validation of pixelated TPC for CEPC TDR

- **Pixelated Readout Electronics: TEPix development**
  - Multi-ROIC chips + Interposer PCB as RDL
  - Four-side buttable
- **TEPix: Low power Energy/Timing measurement**
  - Low power consumption: 0.5mW/ch@2nd Chip
  - Timing: 1 LSB(<10ns)
  - Noise: 300e- (high gain)





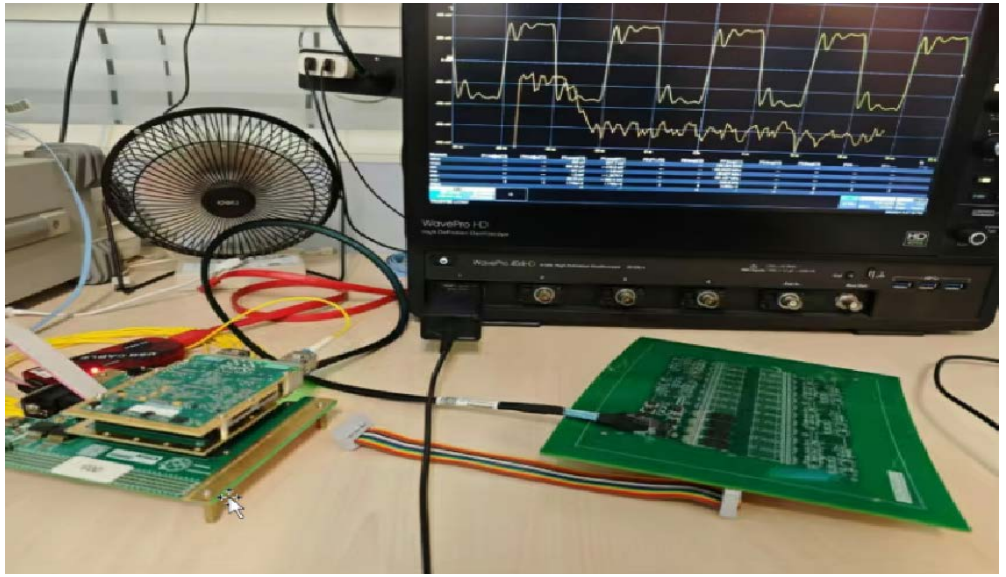
Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns

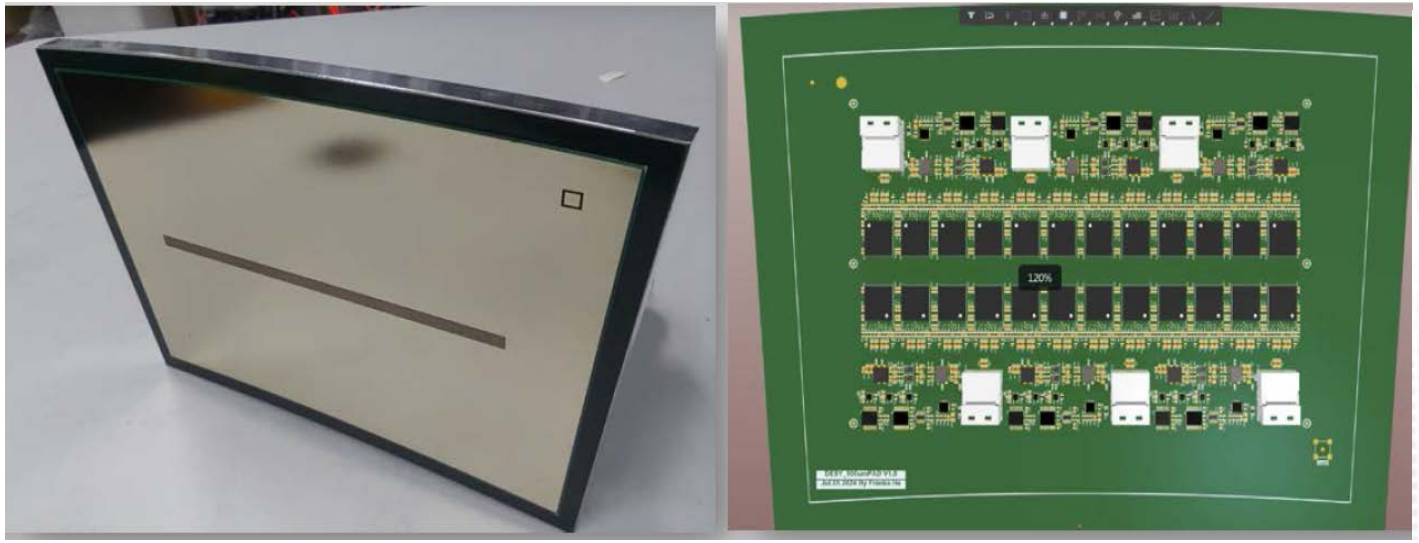


FEE ASIC: TEPIX—Test Results in May

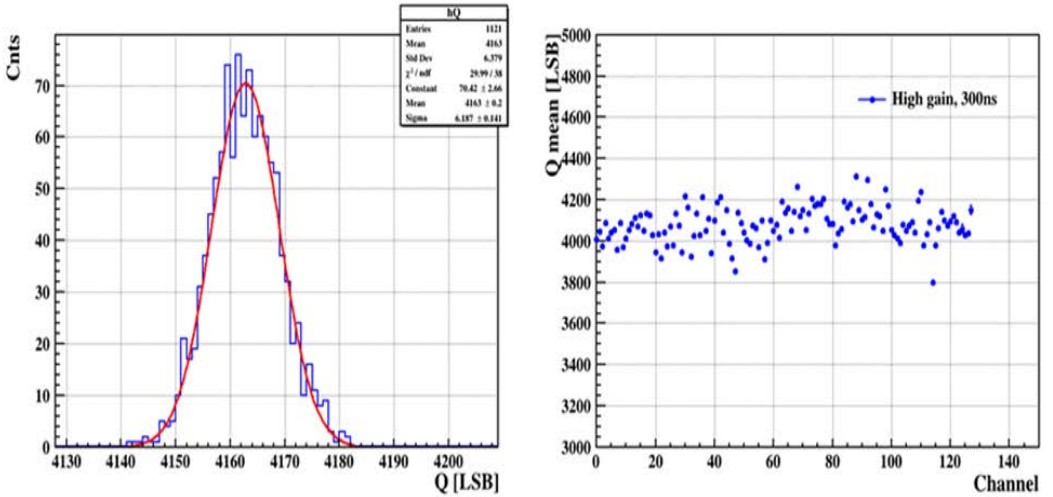
Prototype validation of pixelated TPC for CEPC TDR

- **R&D on Pixelated TPC readout for CEPC TDR.**
  - ASIC chip developed and **2nd 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 in 2024. (December before)**





Photos TPC modules assembled for the beam test



Amplitude (left) and Uniformity/ch (right)

Summary and outlook

- **TPC detector prototype R&D using pad readout towards pixelated readout for the future e+e- colliders, even the high luminosity Z pole running. DC will be as the alternative detector at Tera-Z.**

- **Pixelated TPC is choose as the baseline gaseous tracker in CEPC ref-TDR. The simulation results show the good performance of PID, momentum resolution and tracks. Some validation of TPC prototype have been studies.**

- **Synergies with CEPC/FCCee/EIC/LCTPC allow us to continue R&D and ongoing with the significant international collaboration. All will input to CEPC ref-TDR in next few months.**

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Many thanks!