CEPC Gaseous Track Detector

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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

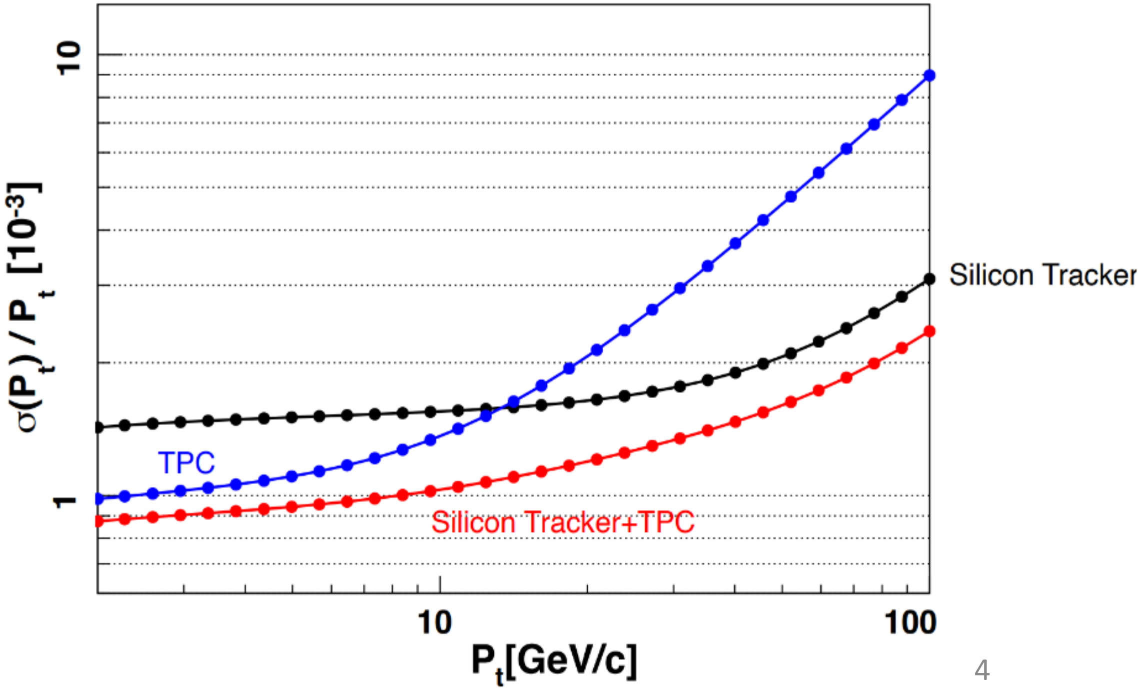
- This talk relates to the CEPC Physics and Detector Ref-TDR.
  - Chapter 5: Gaseous tracker
  - Draft of content listed →

Chapter 5 Gaseous trackers

Physics requirement

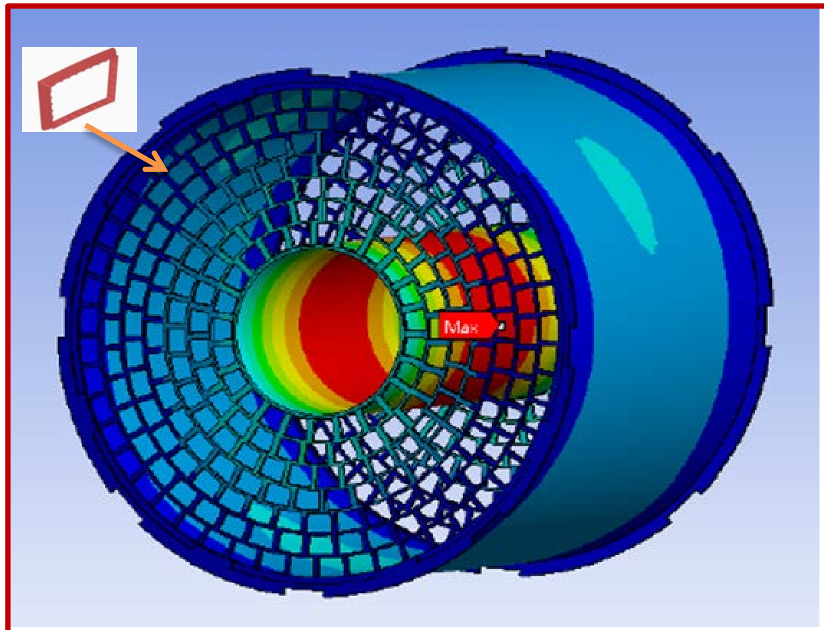
- CEPC operation stages in TDR: **10-years Higgs → 2-years Z pole → 1-year W**
- Phys. Requirements of the track detector
  - Thousands of hits with high spatial resolution compatible with PFA algorithm (low X_0)
- Beneficial for jet & differential at higher energy
  - Highly requirements for excellent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

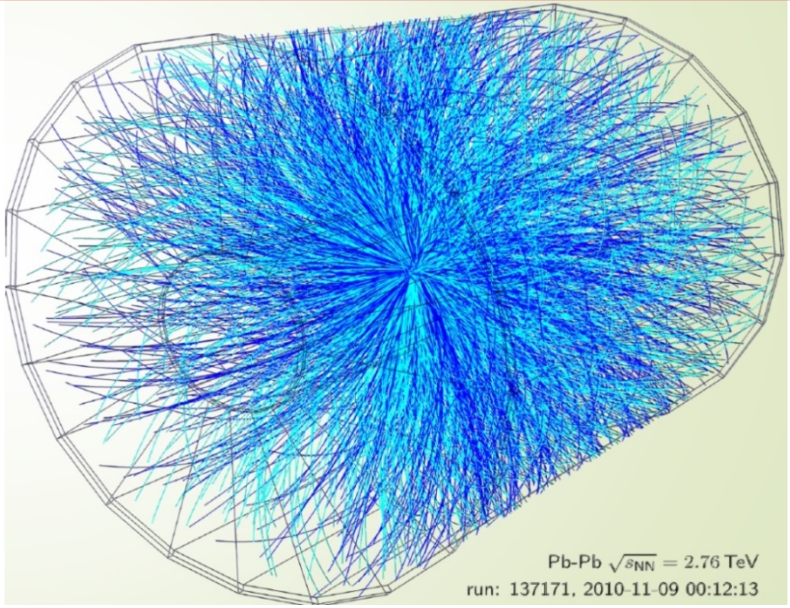


Technology survey and our choices

- 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

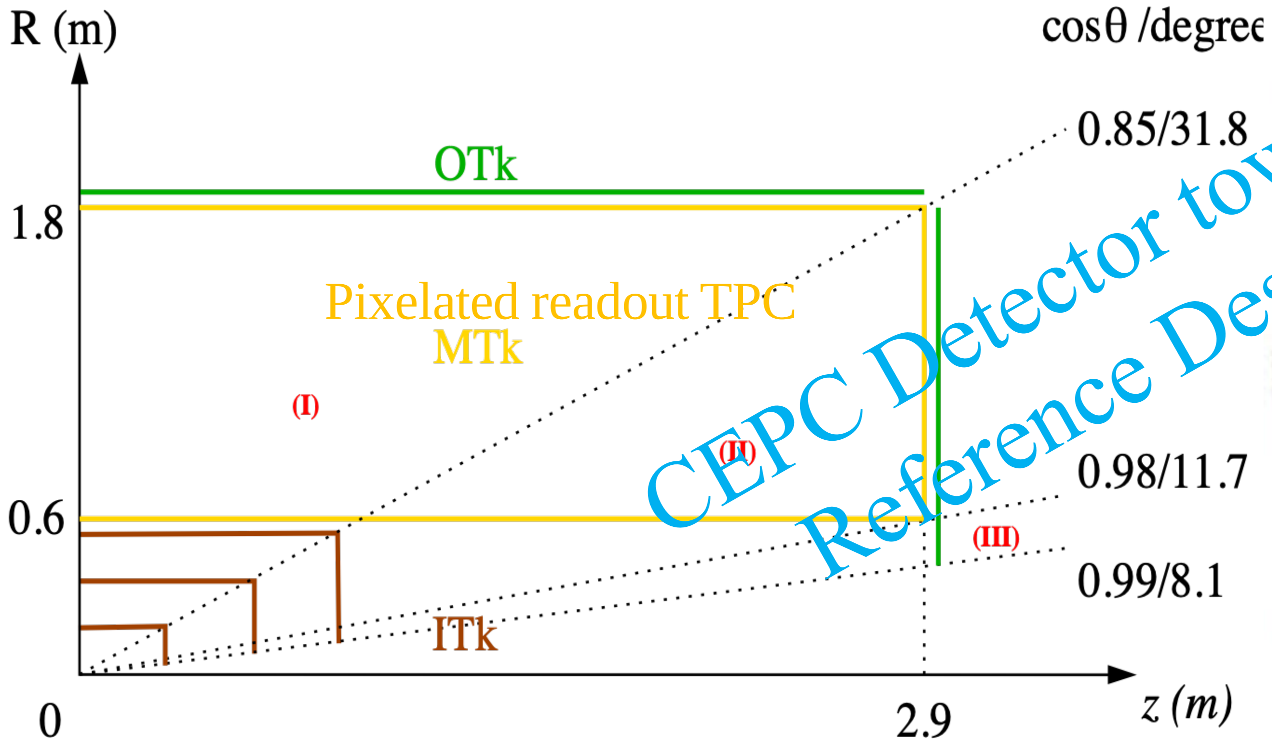


Time Projection Chamber

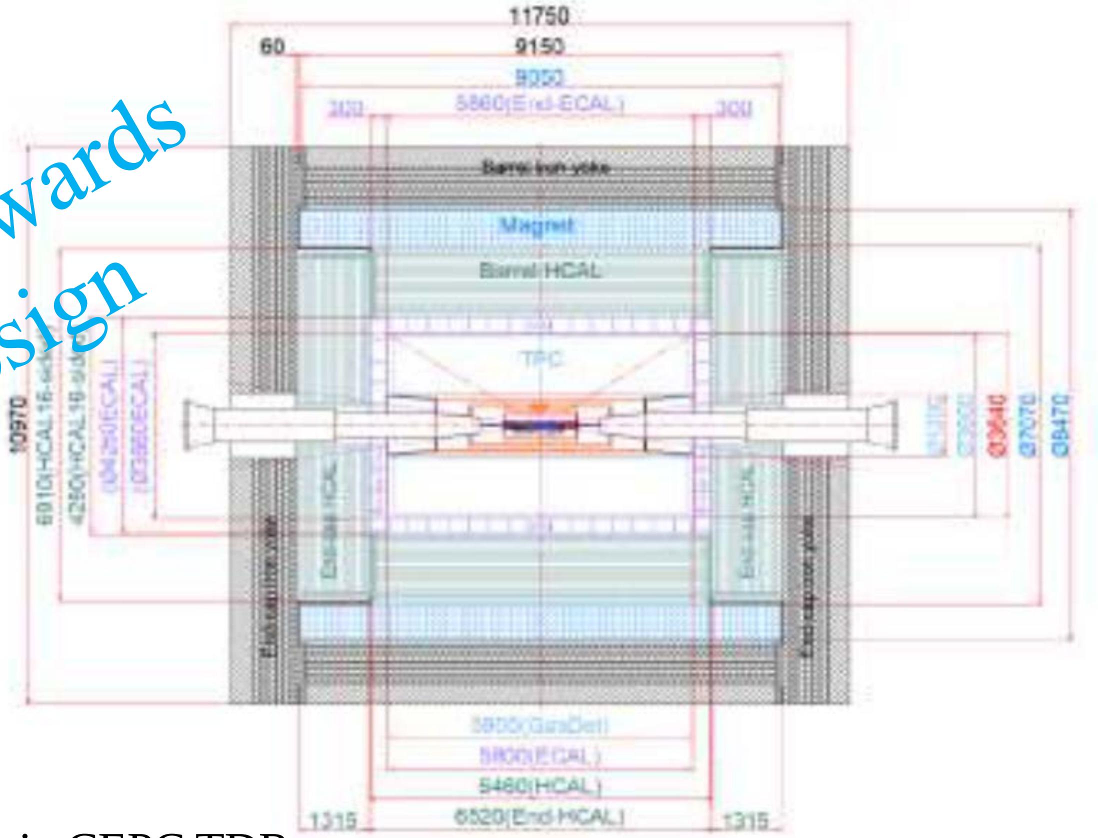

Drift Chamber

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)**

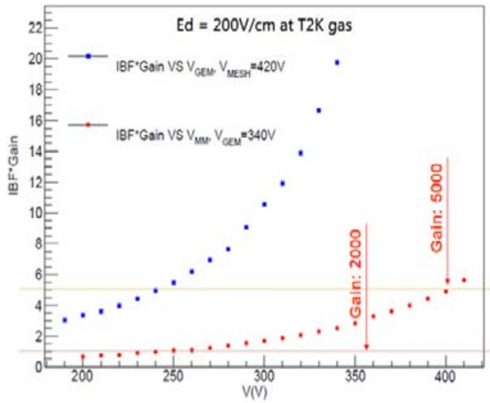
Critical key issues

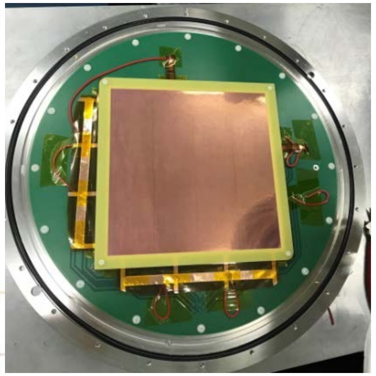
  - **Material budget at endcape/barrel √**
  - **Occupancy and hit density at Tera-Z √**
  - **Ion backflow suppression √**
  - **Running at 2 Tesla √**
  - **Improved PID √**
  - **Reasonable channels(ongoing)**
  - **Reasonable power consumption (ongoing)**

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

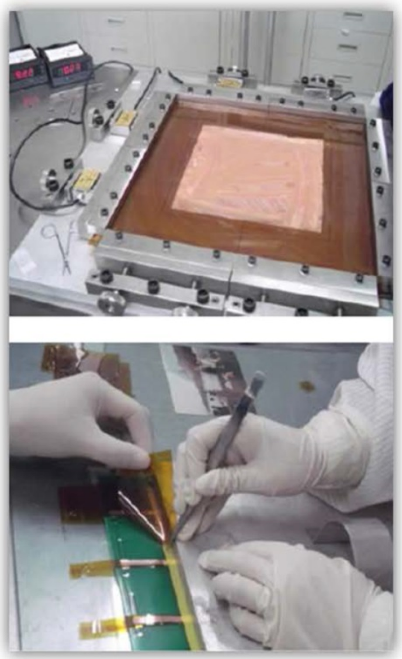
TPC prototype R&D efforts and results

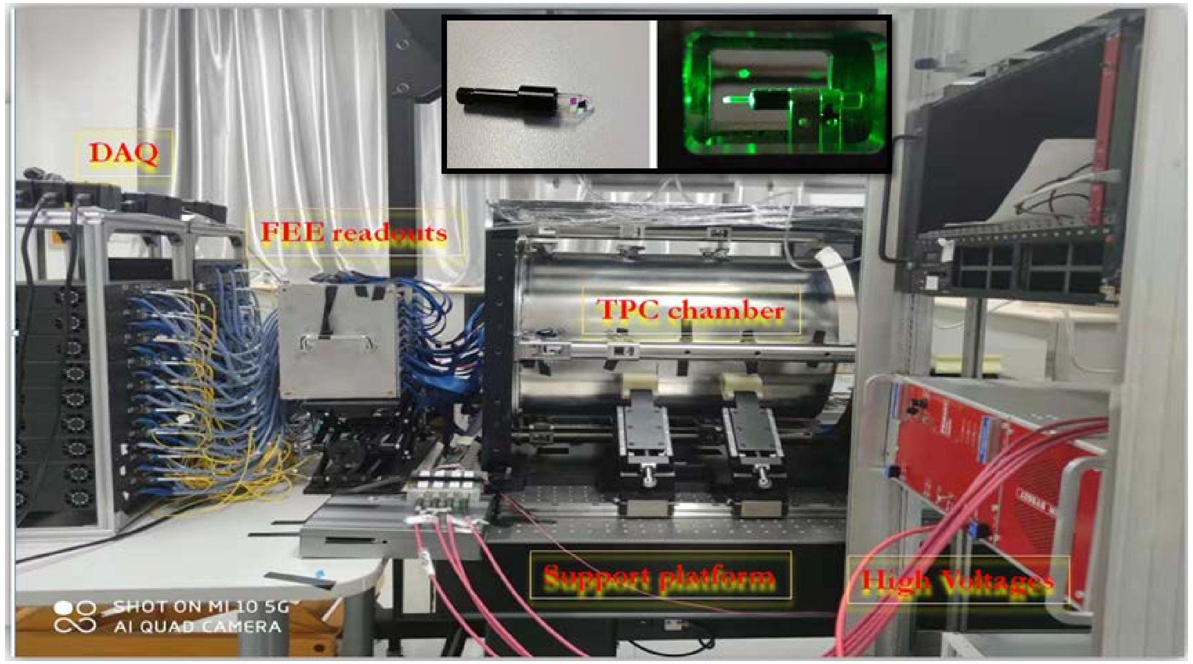
- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to **TPC prototype R&D for Higgs and Tera-Z**
- **Achievement by far:**
  - **IBF×Gain ~1 @ G=2000** validation with hybrid TPC module
  - Spatial resolution of **$\sigma_{r\varphi}$≤100 μm and dE/dx resolution of 3.6%**
  - FEE chip: reach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



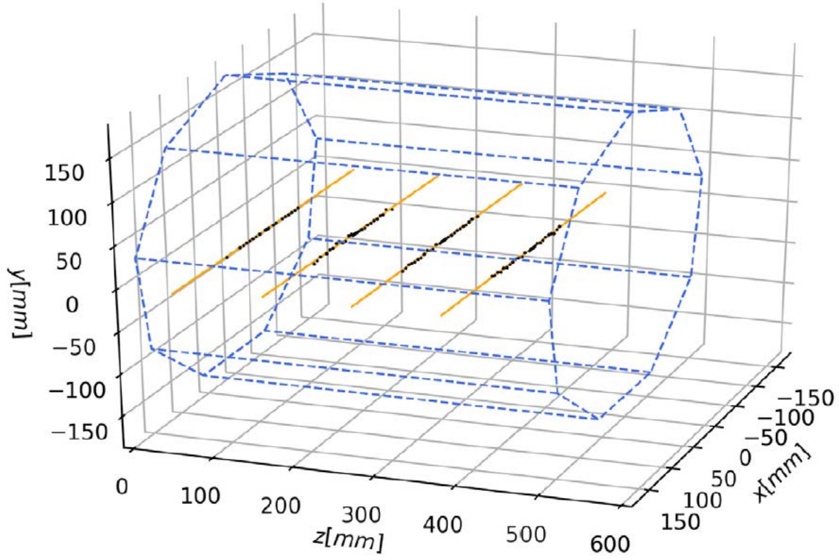


Ion suppression TPC module R&D





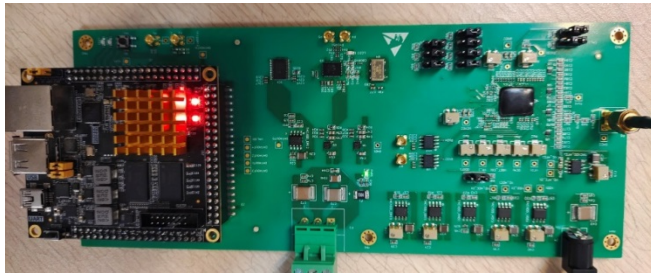
TPC prototype with integrated 266nm UV laser

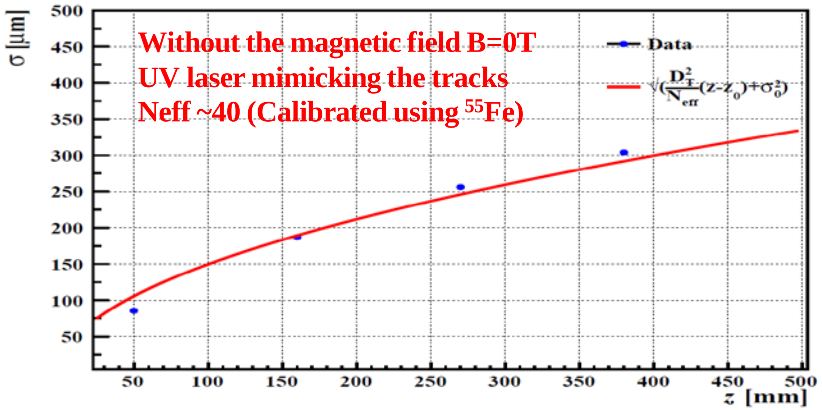


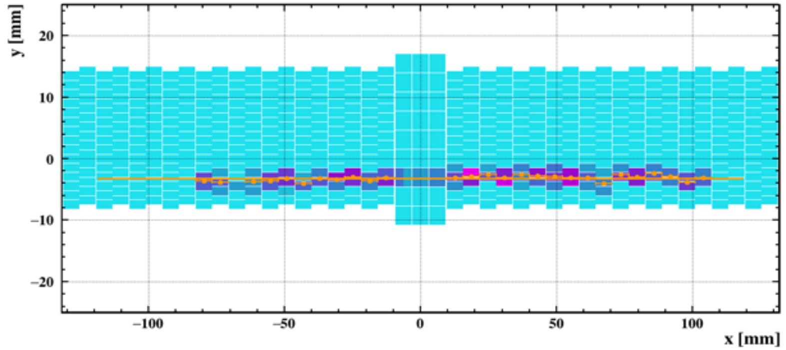
Tracks reconstruction

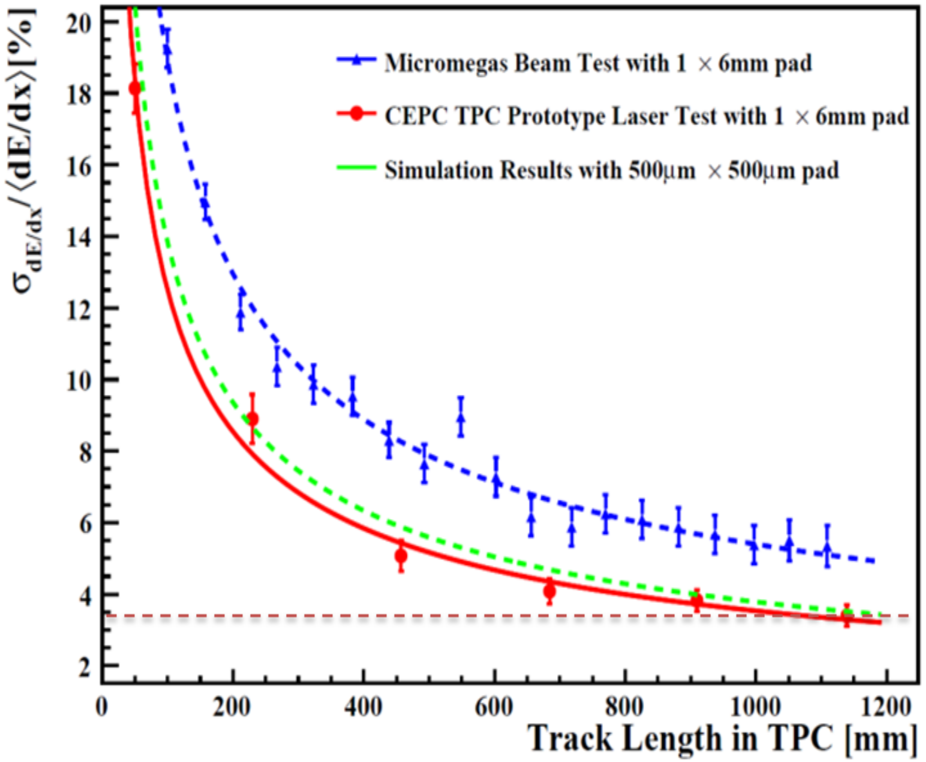
Highlights of TPC prototype R&D

- **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









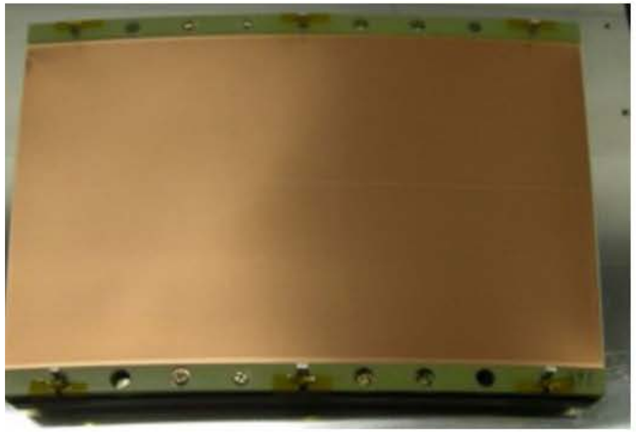
Publications by CEPC TPC group in 2018-2024:

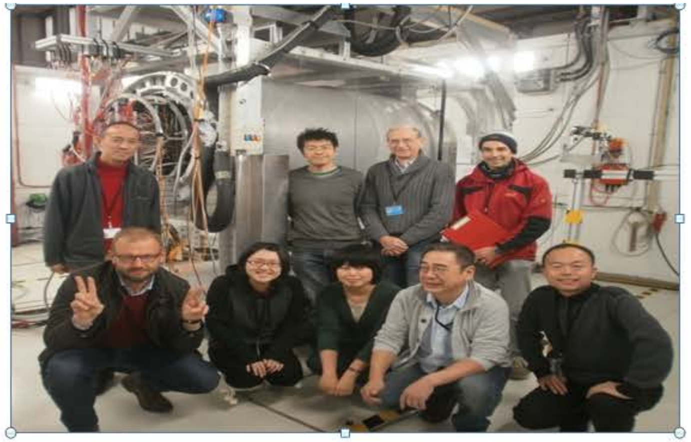
- https://doi.org/10.1088/1748-0221/18/08/E08002
- https://doi.org/10.22323/1.449.0553
- https://doi.org/10.1016/j.nima.2022.167241
- https://doi.org/10.1109/NSS/MIC44867.2021.9875566
- https://doi.org/10.1109/NSS/MIC44845.2022.10399097
- https://doi.org/10.1088/1748-0221/15/09/C09065
- https://doi.org/10.1088/1748-0221/15/05/P05005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

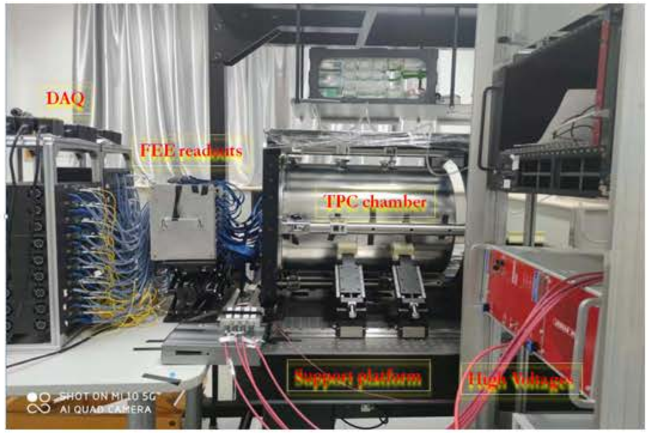
Activity international collaboration

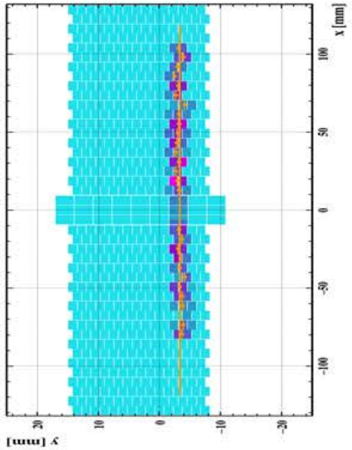
- **Activity collaboration:** Pixelated readout and Pad readout from IHEP and LCTPC collaboration
  - Large Prototype setup have been built to compare different detector readouts for Tera-Z
  - PCMAG: B < 1.0T, bore Ø: 85cm, Spatial resolution of $\sigma_{r\phi} \leq 100$ μm
  - Collaboration implement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

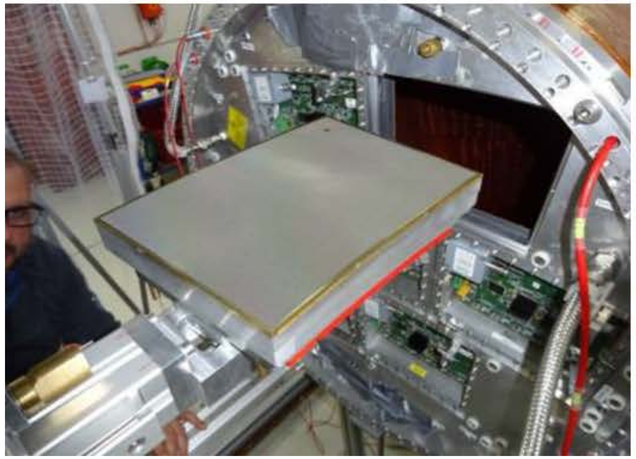
ArXiv. (2023)2006.08562
NIM A (2022) 167241
ArXiv (2022)2006.085
JINST 16 (2021) P10023
JINST 5 (2010) P10011
NIM A608 (2009) 390-396

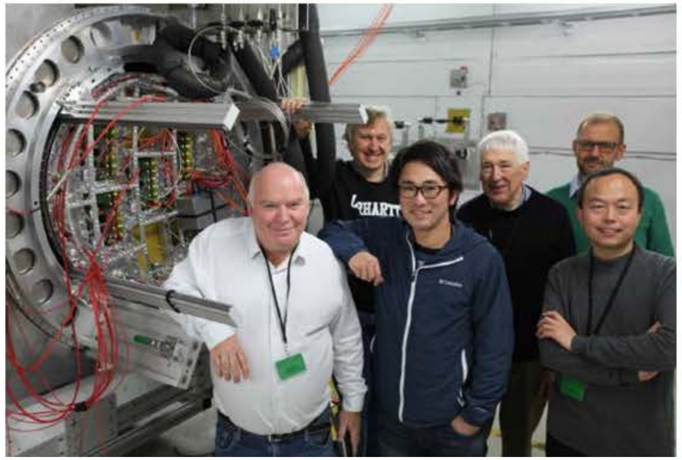


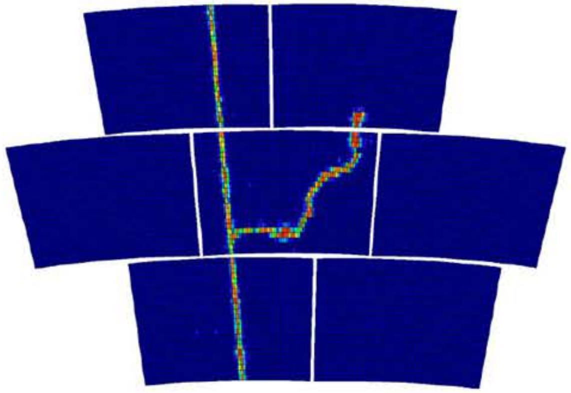








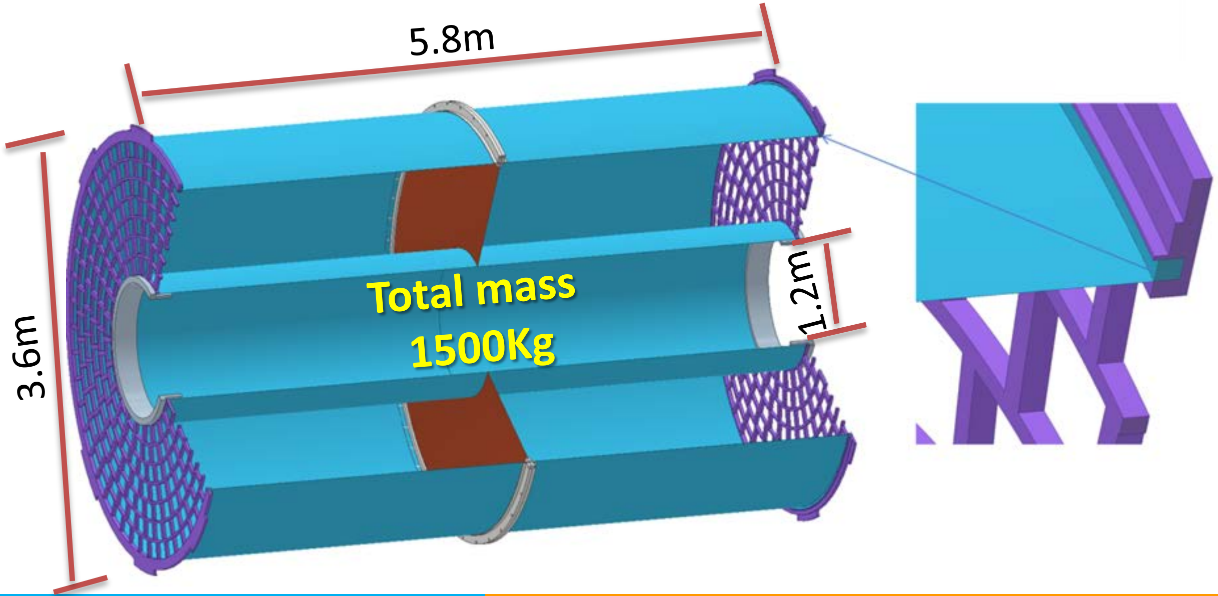


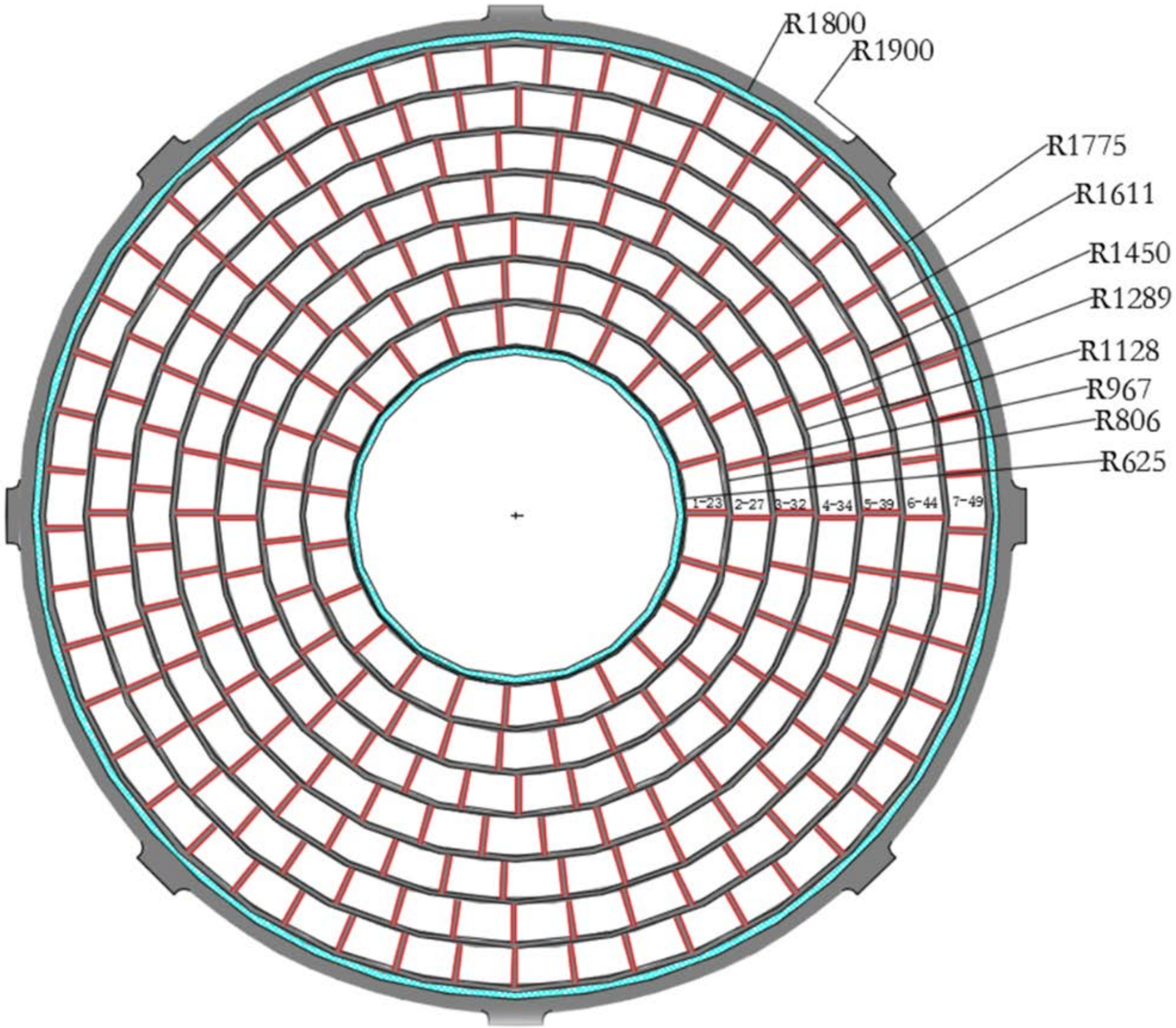


Detailed design and performance of Baseline: TPC

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	25μs @ 2.75m
Pixelated detector	Pixelated Micromegas

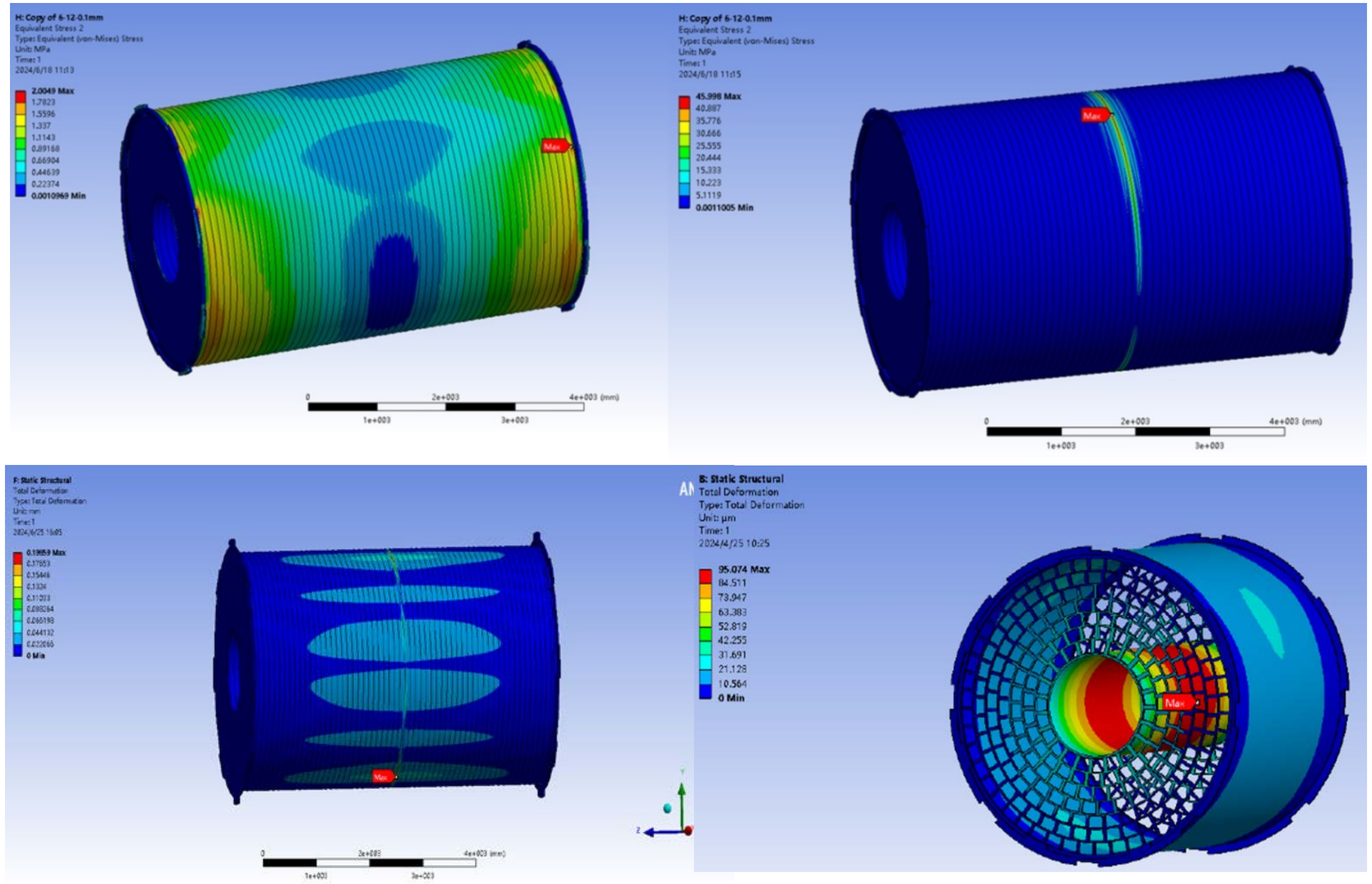




Detailed design of TPC detector in ref-TDR

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 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**

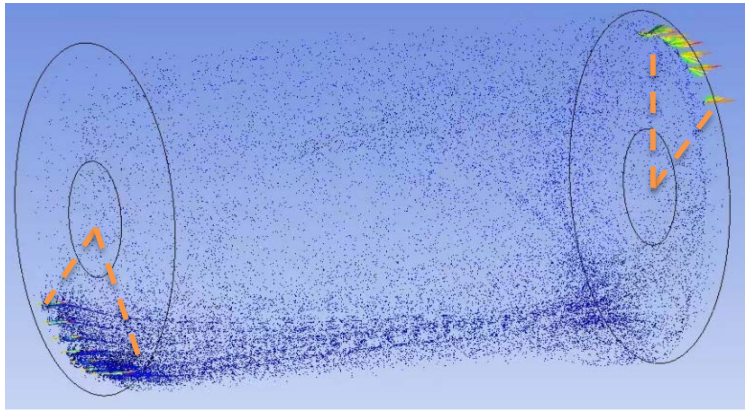
- **Low material of the TPC endcap**

15%X_0 in total, including

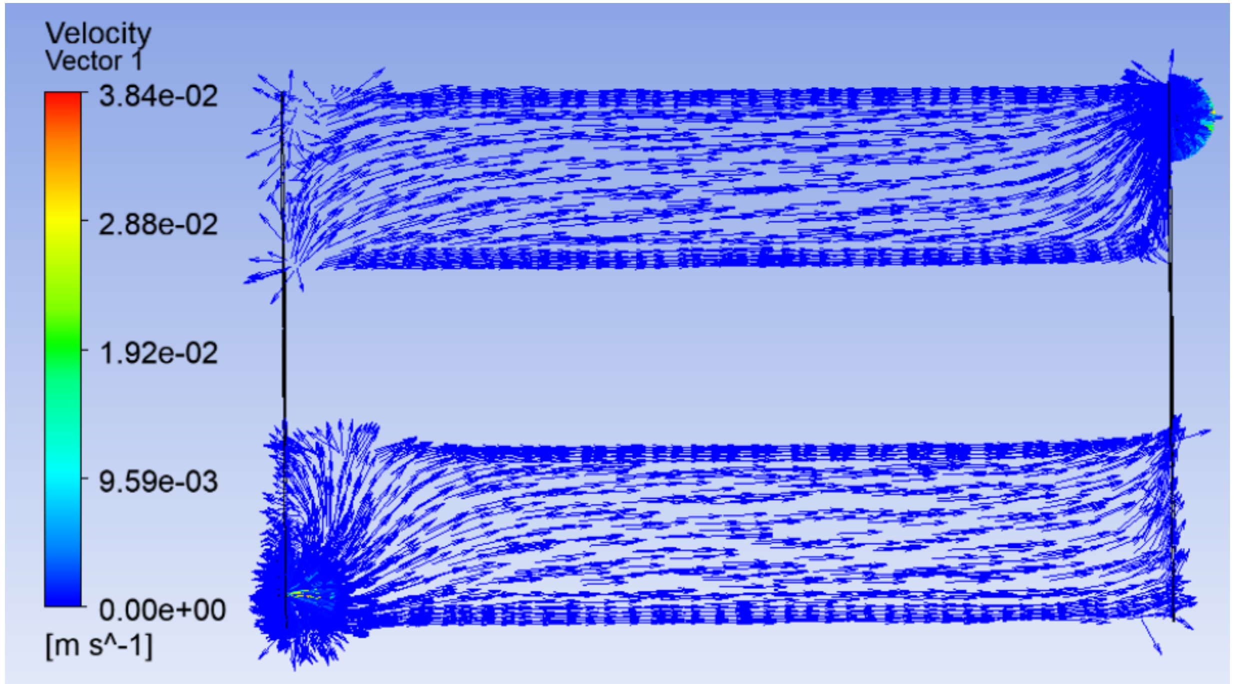
Readout plane, front-end-electronics	4%
Cooling	2%
Power cables	9%

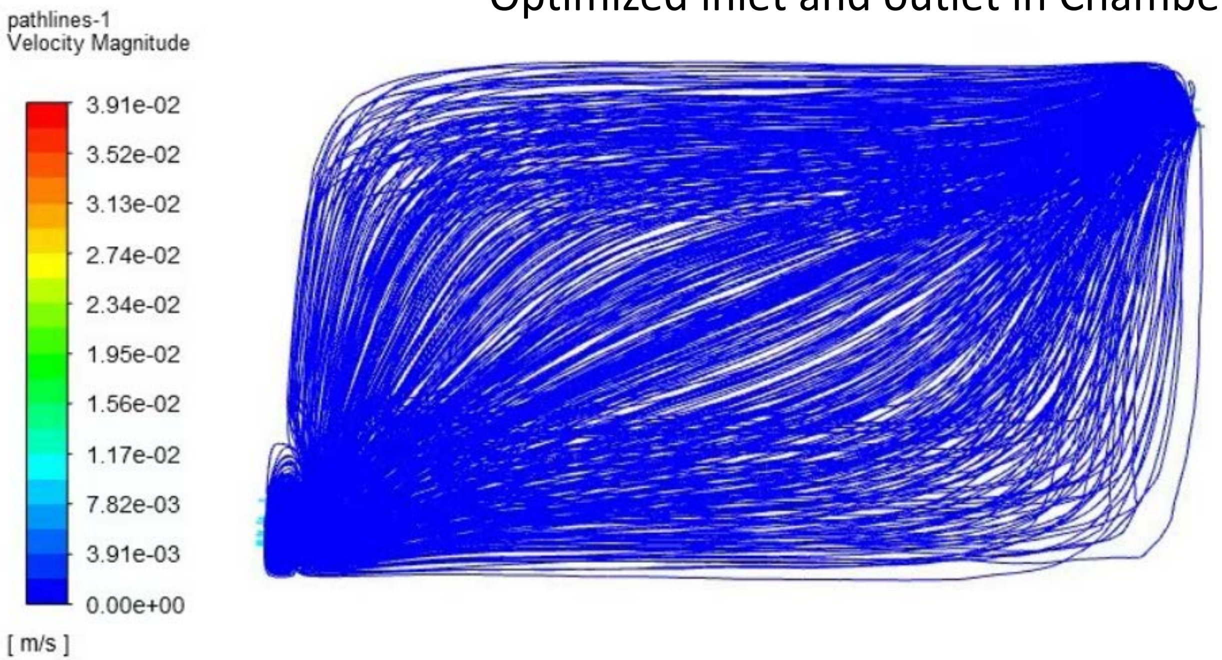
Optimization of Gas flow in Chamber

- 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

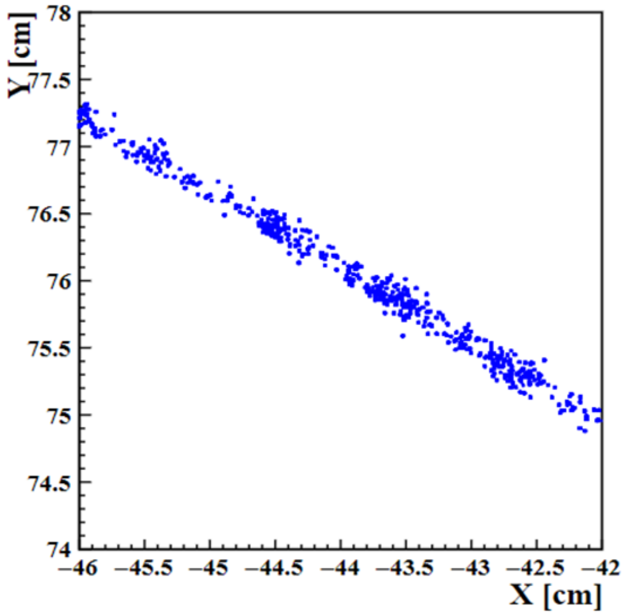




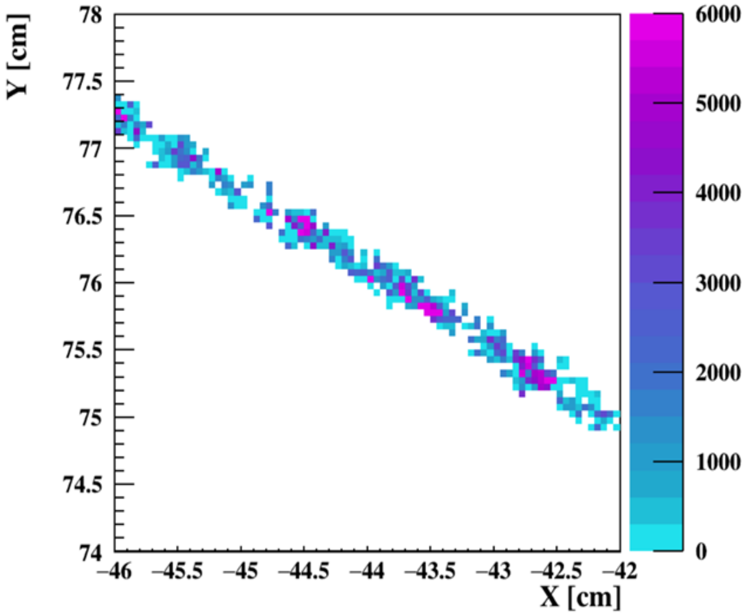
Simulation of gas flow and uniformity distribution in TPC Chamber

Optimization of the readout size

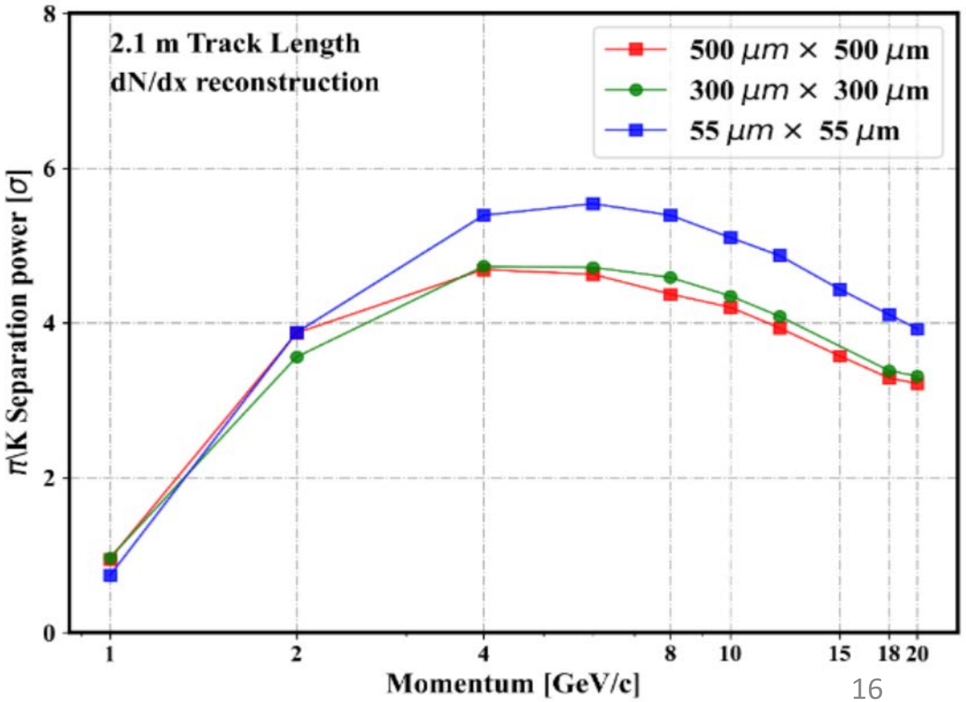
- Timepix (55μm×55μm) readout TPC prototype has been validation four times on DESY beams.
  - Power consumption: 2W/cm^2 ; Low power mode: 1W/cm^2 (**Too high power for pixelated readout**)
- Simulation results showed that readout size can be optimized at 300μm-500μm.
  - Reasonable readout channels 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)



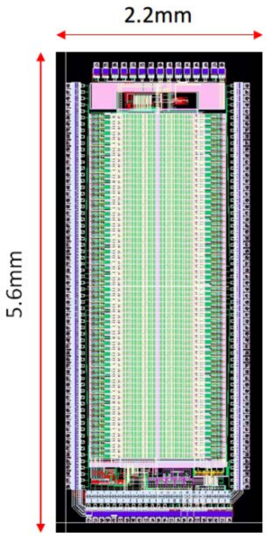
pixel response (500 μm× 500 μm)



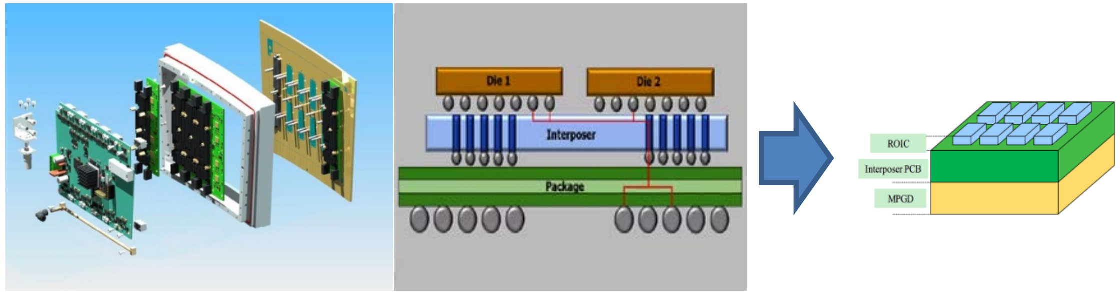
DOI: 10.1088/1748-0221/15/02/T02001
DOI: 10.1088/1748-0221/15/05/P05005

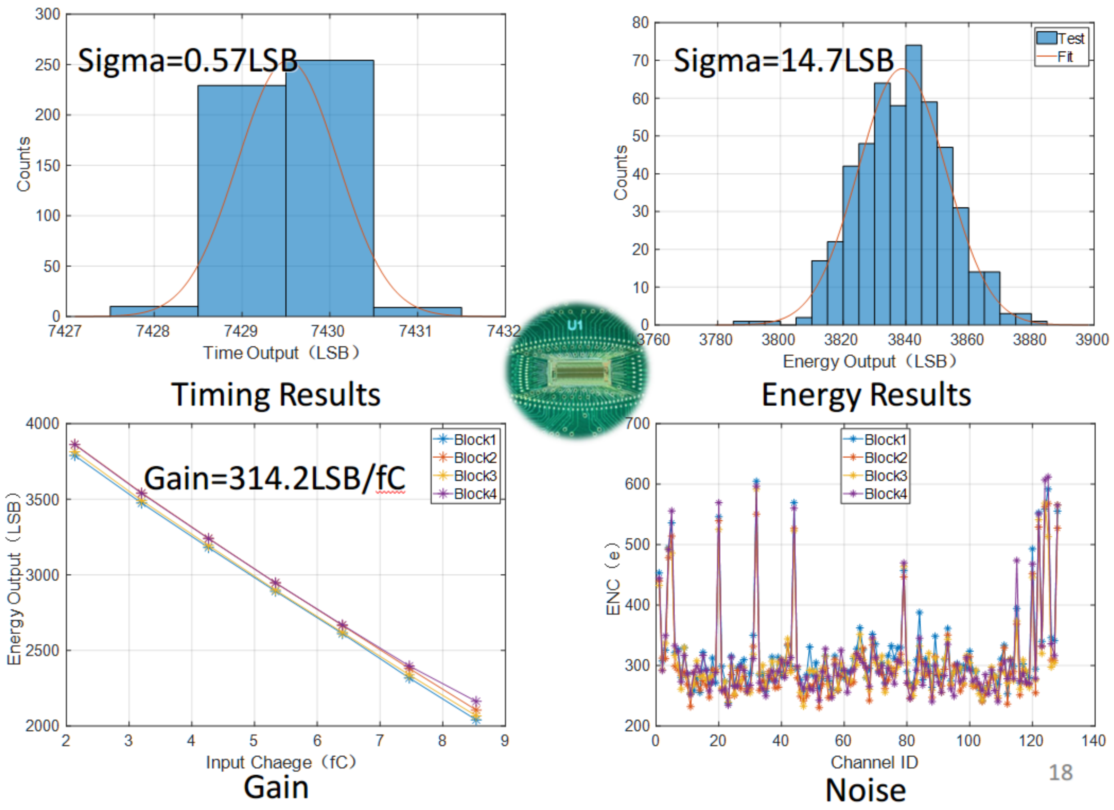
Detailed design of electronics and BEC

- 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

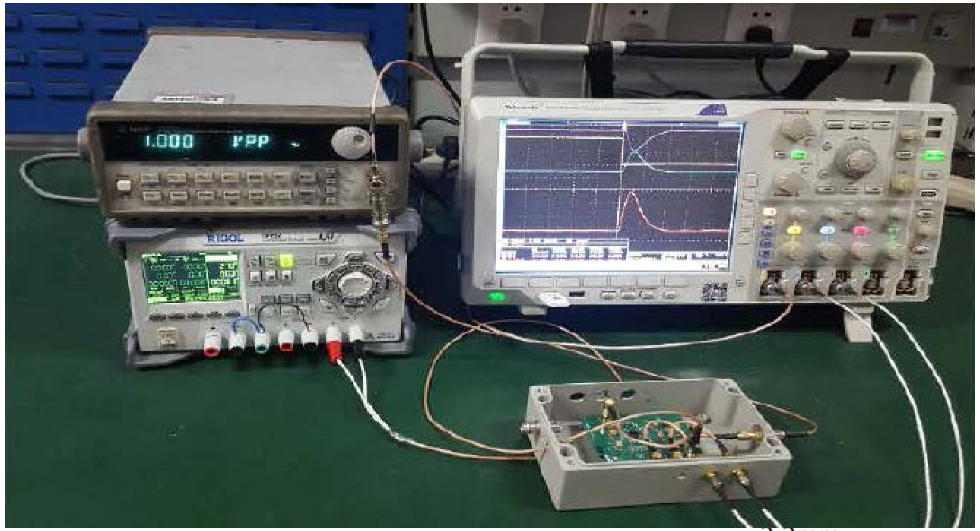


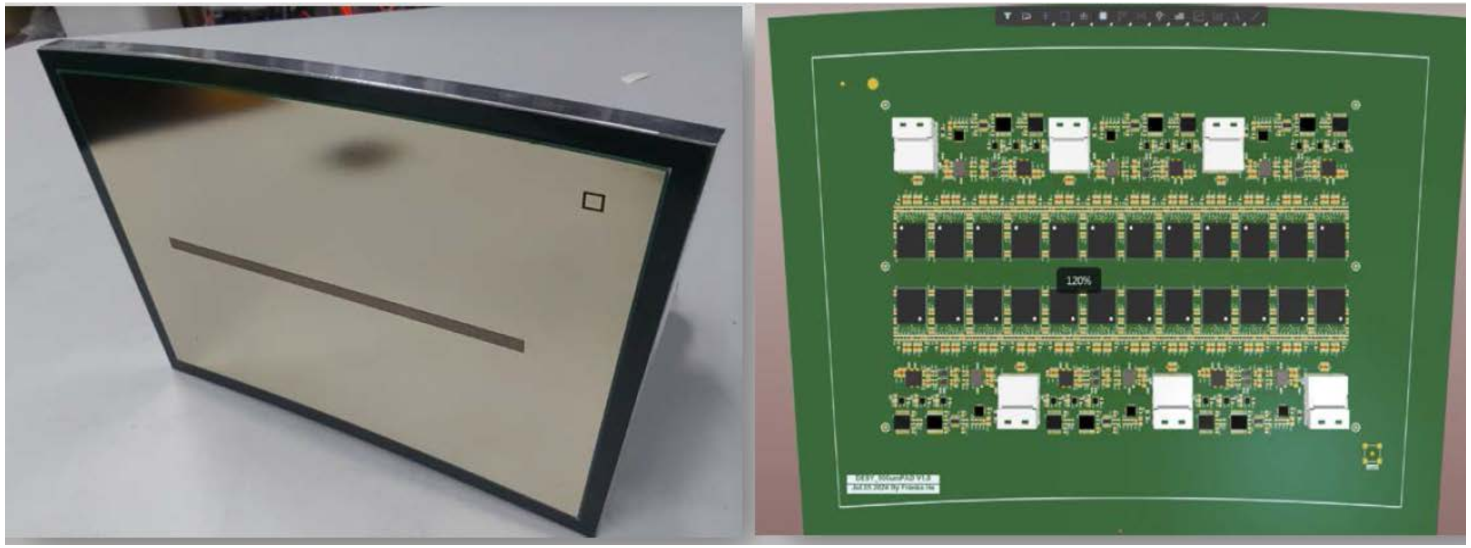


FEE ASIC: TEPIX—Test Results in May

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

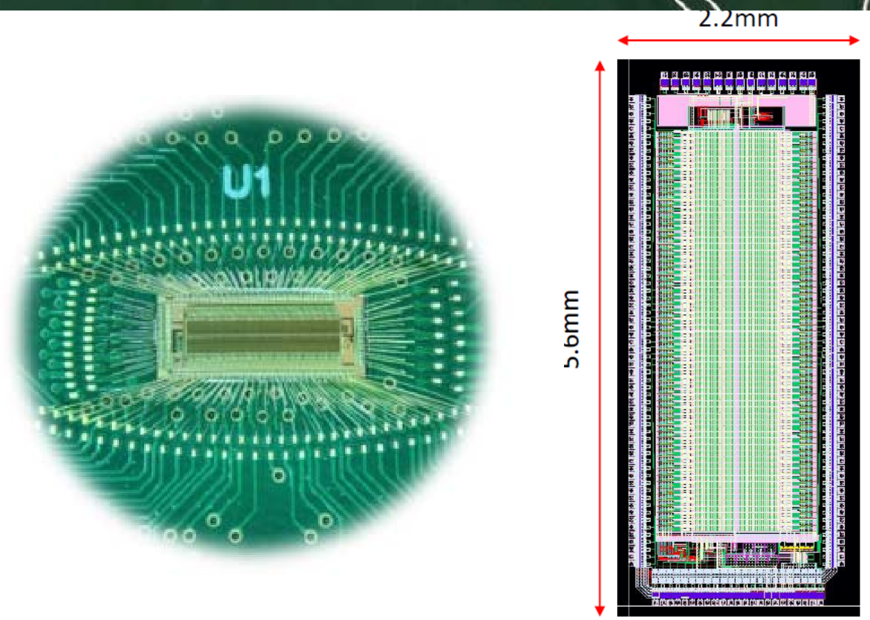
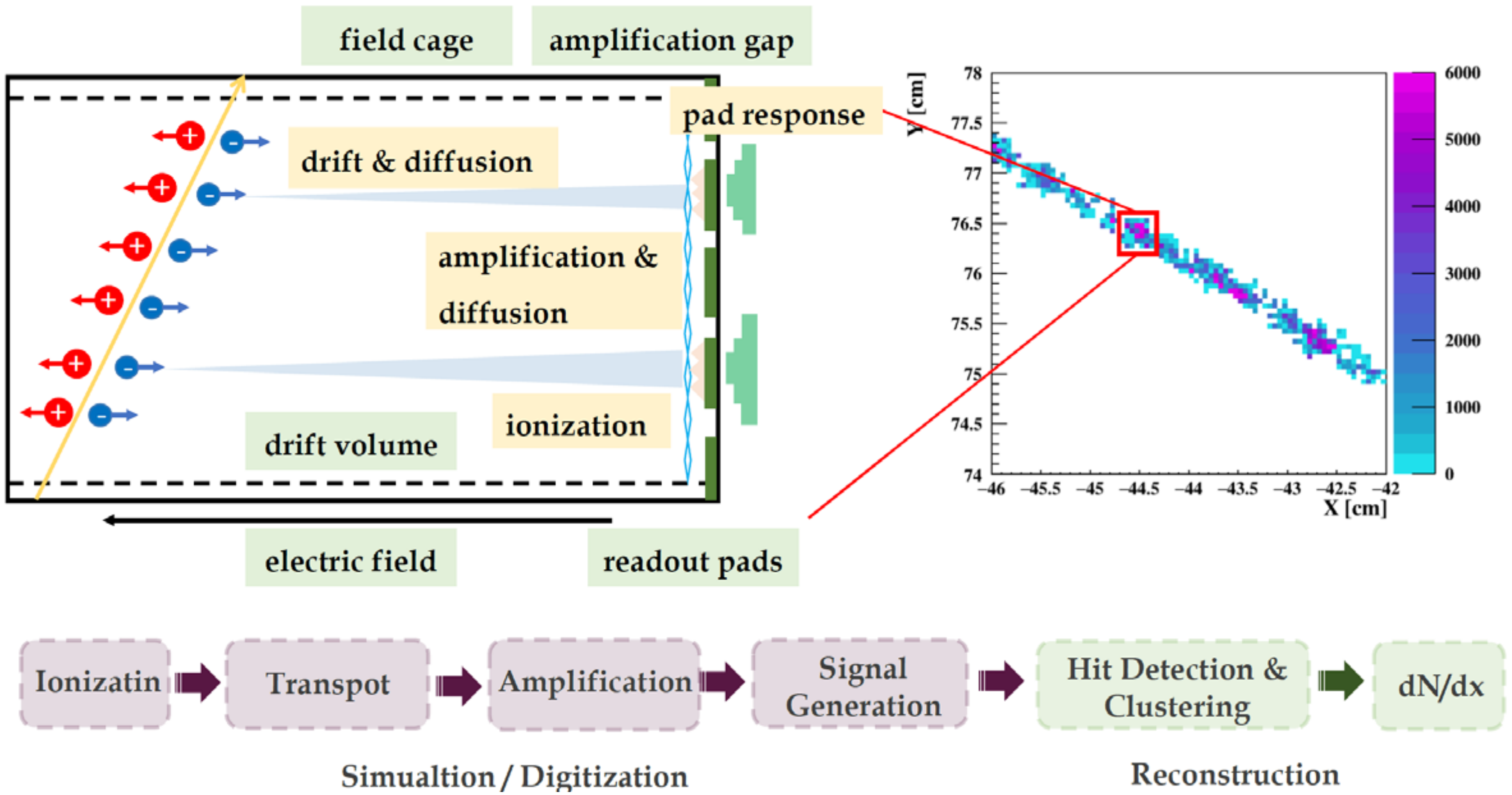
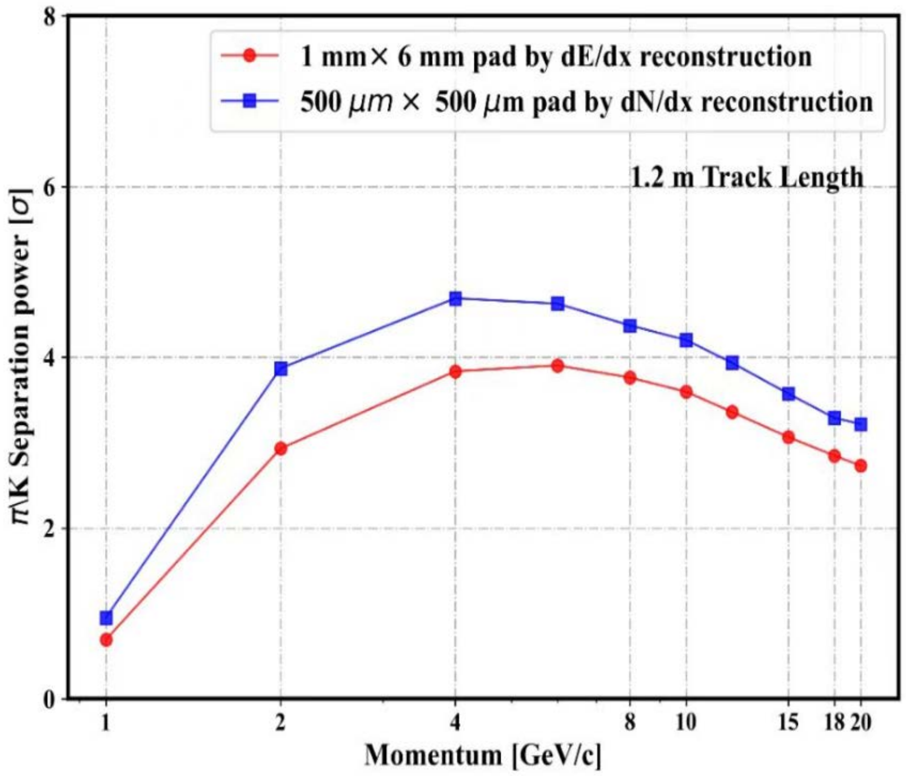


Photo and layout of ASIC Chip R&D for TPC

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**





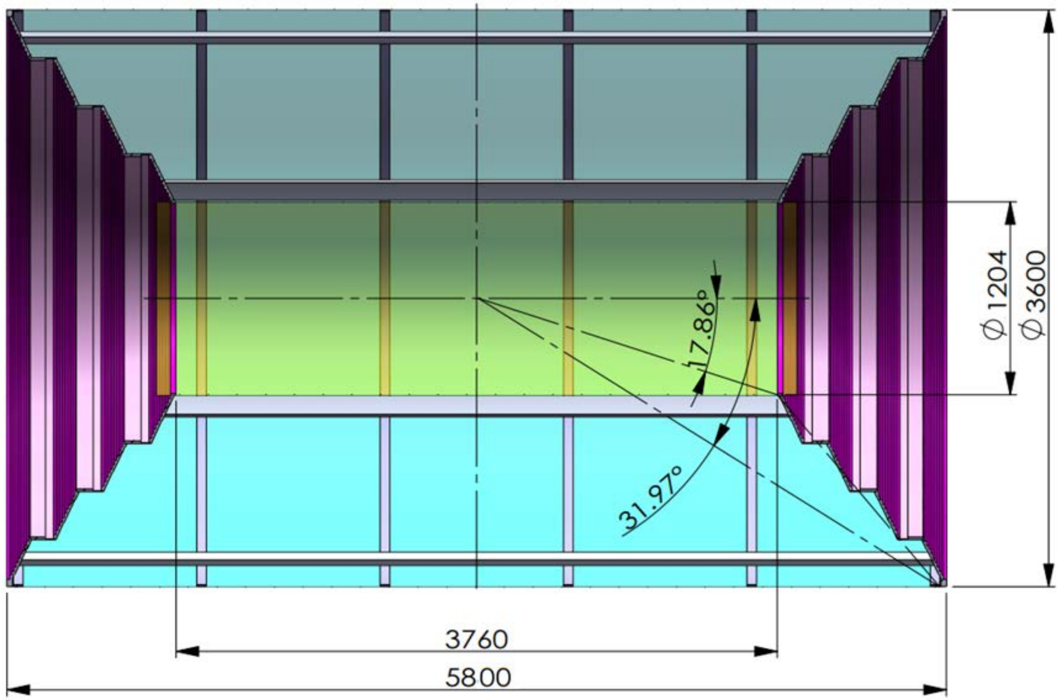
Simulation of TPC detector under 3T/2T and T2K mixture gas

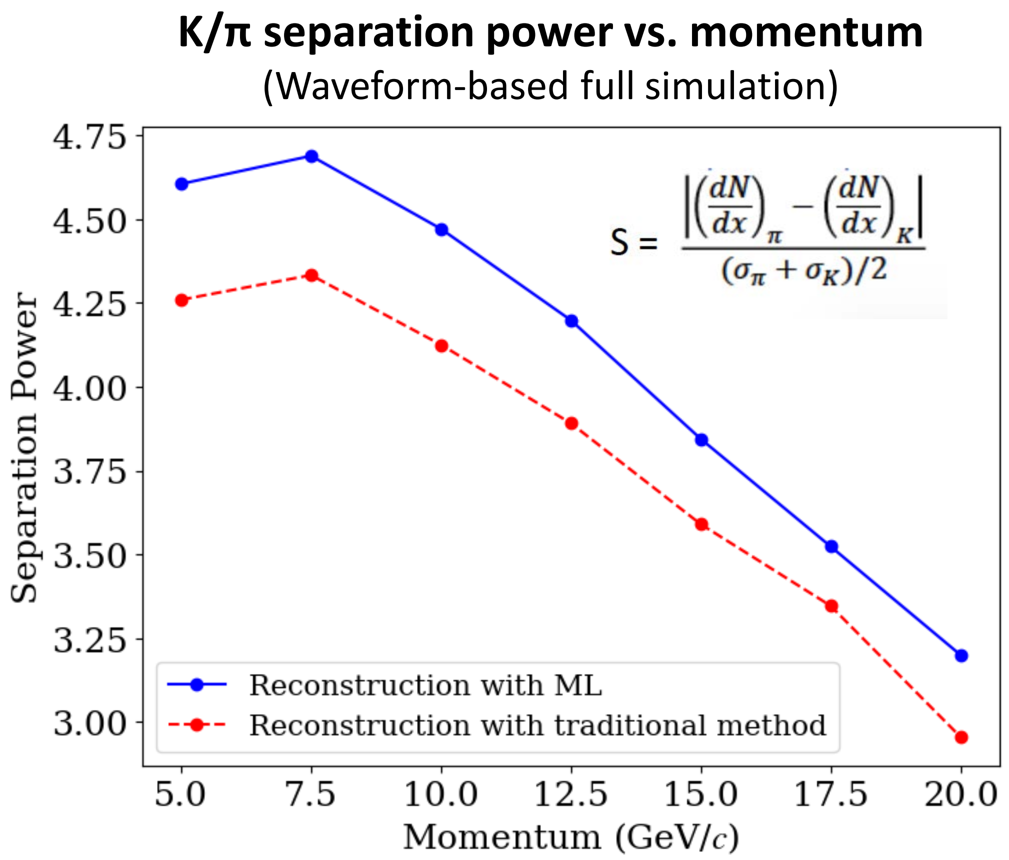
Cite#11: DOI: 10.22323/1.449.0553
Cite#12: EPS-HEP 2023 talk by Yue Chang

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

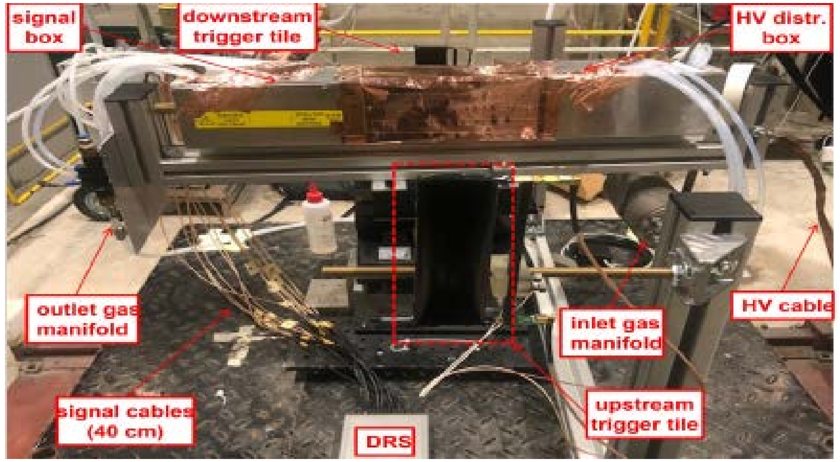


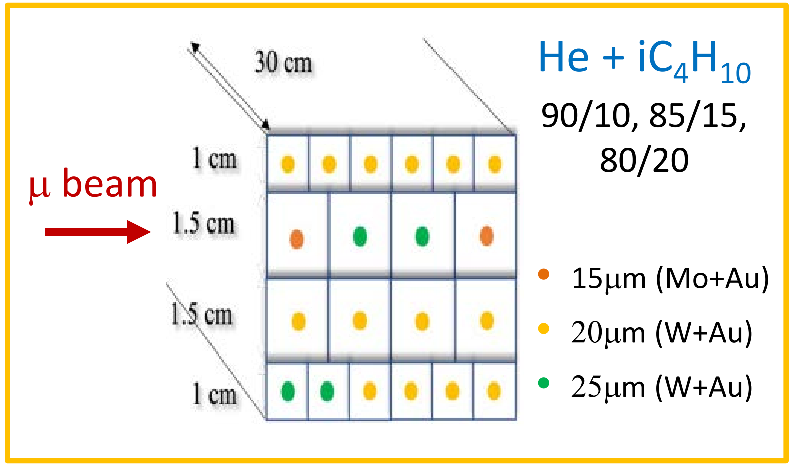


- CF frame structure
- Length: 5800 mm; Outer diameter: 3600 mm; Inner diameter: 1200 mm
- Thickness of each end plate: 20 mm, weight: 880 kg
- Gas mixture: He + iC_4H_{10} (90/10)
- Cell size: 18mm x 18mm, number of cells: 26483
- Material: 0.16% X_0 for Gas+Wires, 0.21%X_0 for inner and outer cylinders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

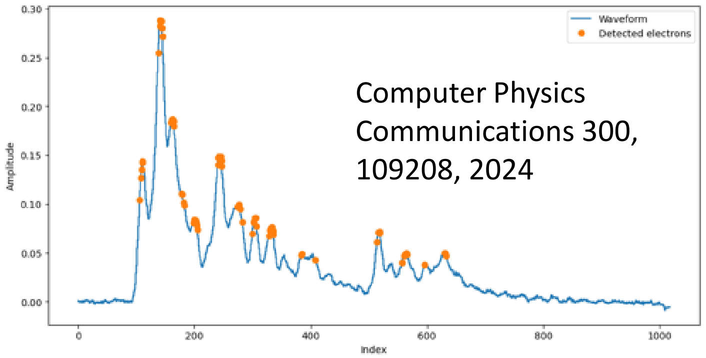
International collaboration of DC

- **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





Waveform reconstruction with ML (domain adaptation)



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 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

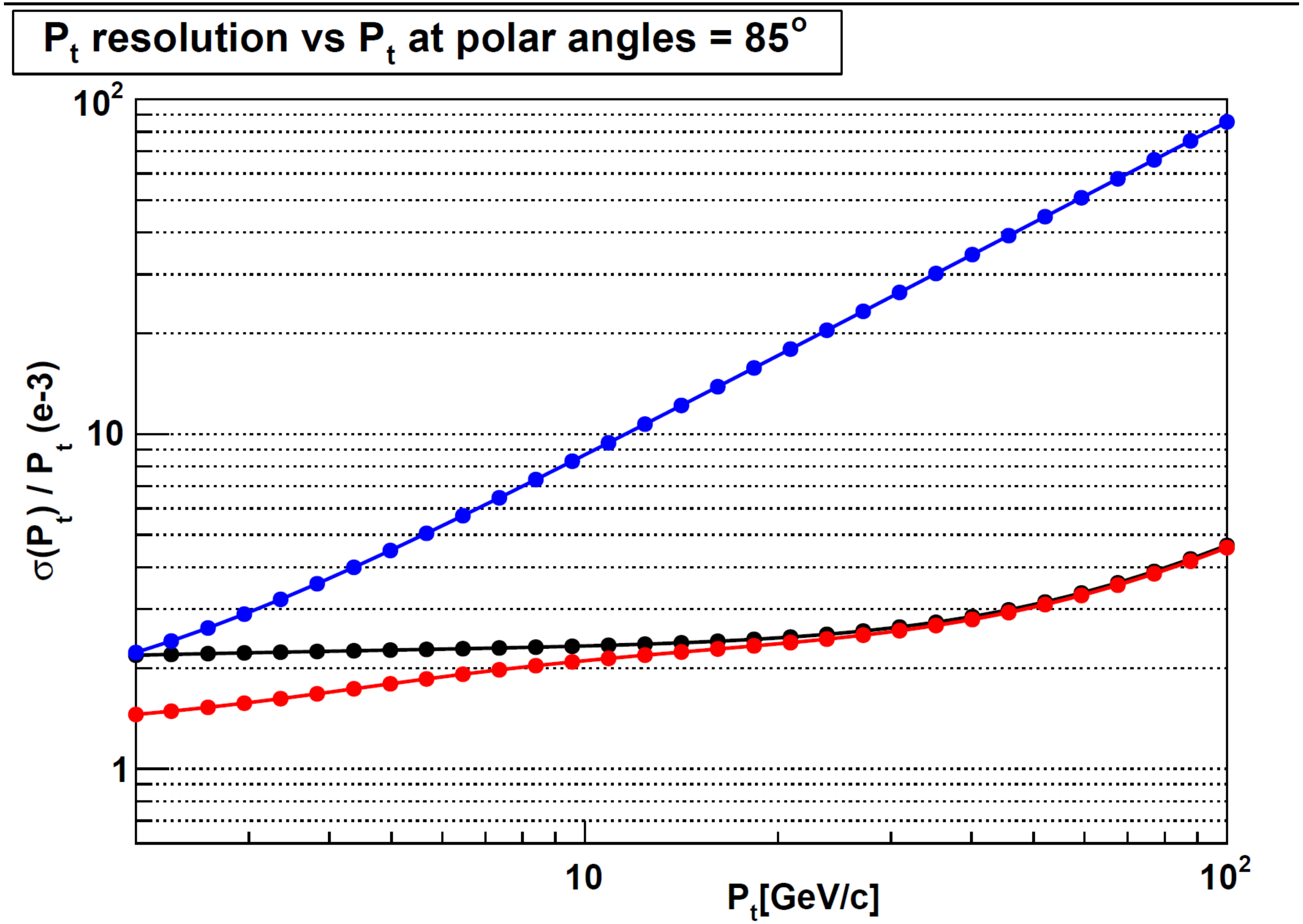
- TPC detector prototype R&D using the pad readout towards the pixelated readout for the future e^+e^- colliders, espial to the high luminosity Z pole run at future e^+e^- collider. DC will be as the alternative detector at Tera-Z.
- Pixelated TPC is choose as the baseline detector as main track in CEPC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

Thank you for your attention!

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Backup of TPC R&D

Physics requirement



Physics requirement - 2

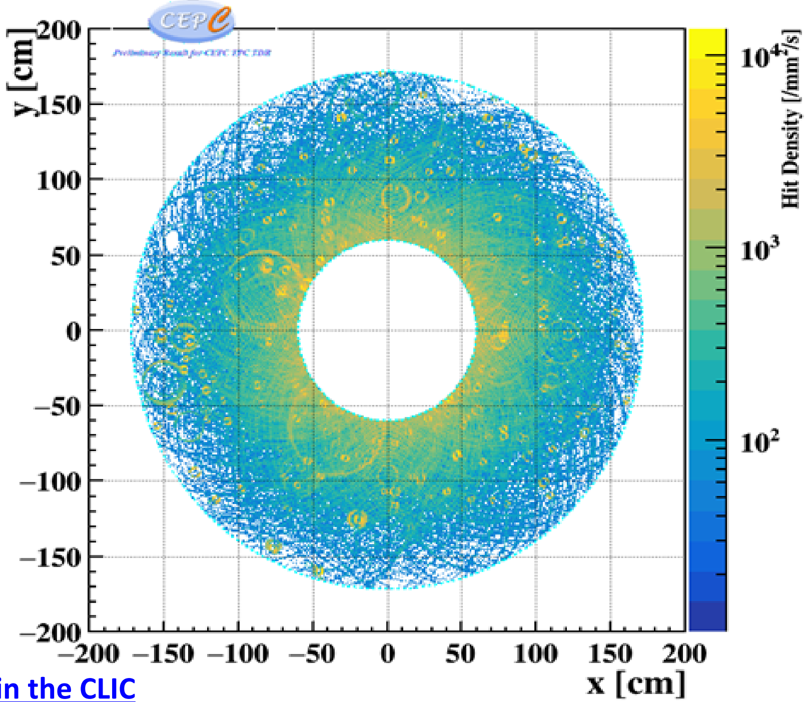
- CEPC operation stages: **10-years Higgs → 2-years Z pole → 1-year W**
- CEPC phy./det. TDR (preparation)
  - Physics and detector concept designed under the principle.
  - Requirements may be with regard to runs of Higgs and Z-pole separately.
    - Mandatory requirements MUST be met.
    - Detector should primarily meet Higgs and run at Z also.

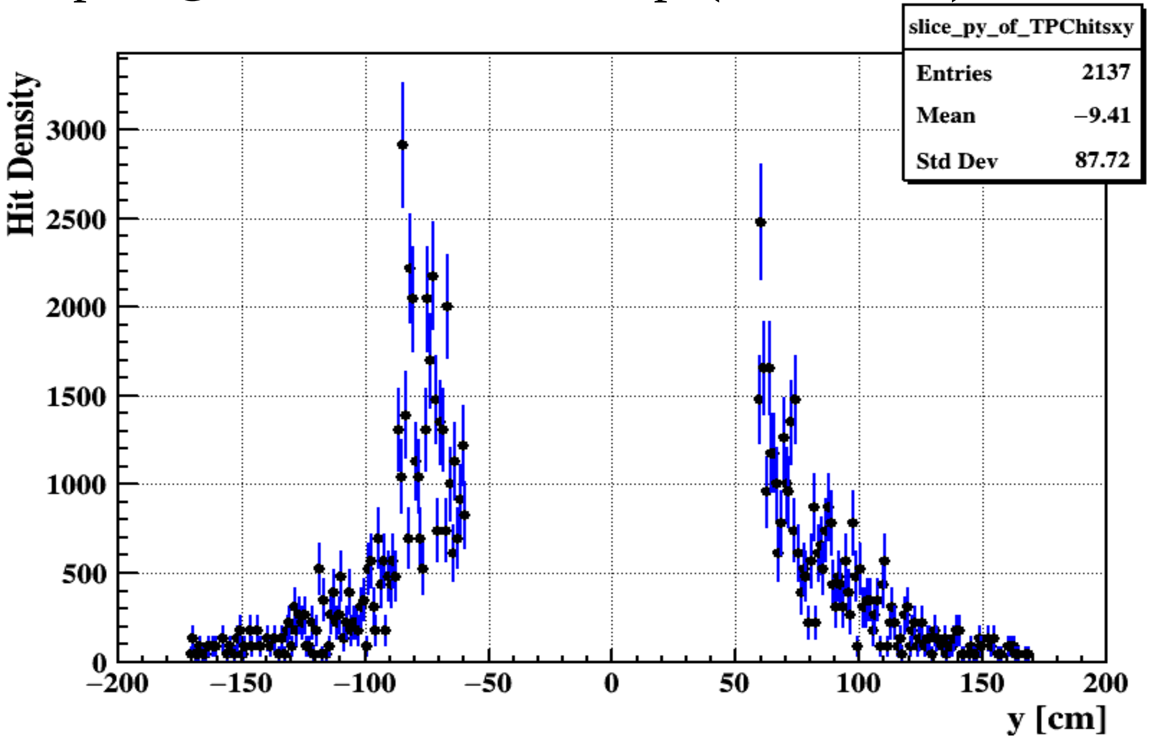
Chapter 3 of this report outlines that the CEPC is planned to be in operation for 8 months annually, totaling 6,000 hours. This operational schedule is used to calculate the cumulative absorbed doses for magnet coil insulations, as illustrated in Figure 4.2.4.16, considering a 10-year Higgs operation, 2-year Z operation, and 1-year W operation. Figure 4.2.4.17 displays the absorbed doses when an additional 5-year $t\bar{t}$ operation is included. These plots also include the upper limit for absorbed dose in epoxy resin, which is measured at 2×10^7 Gy [11].

CEPC- TDR p116

Occupancy/hits desnity R&D and results

- **Low voxel occupancy** : 1E-5 to 1E-6 (cite#1)
- At 2 E36 with Physics event only, even bunch distribution(cite#2).
    - Pixelated readout much **LOWER** inner most occupancy (**0.6m inner radius**)
    - Pixelated readout can easily handle a high hits rate at Z pole. (cite#3)
    - The data at the inner radius @40M BX Z pole@1 Module ~0.05Gbps(Maximum).

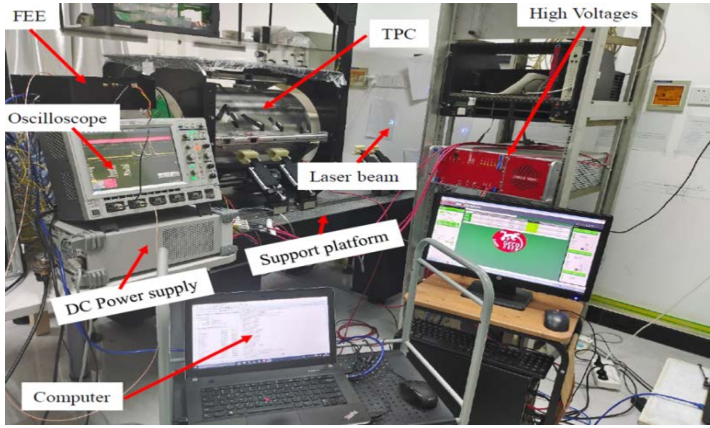


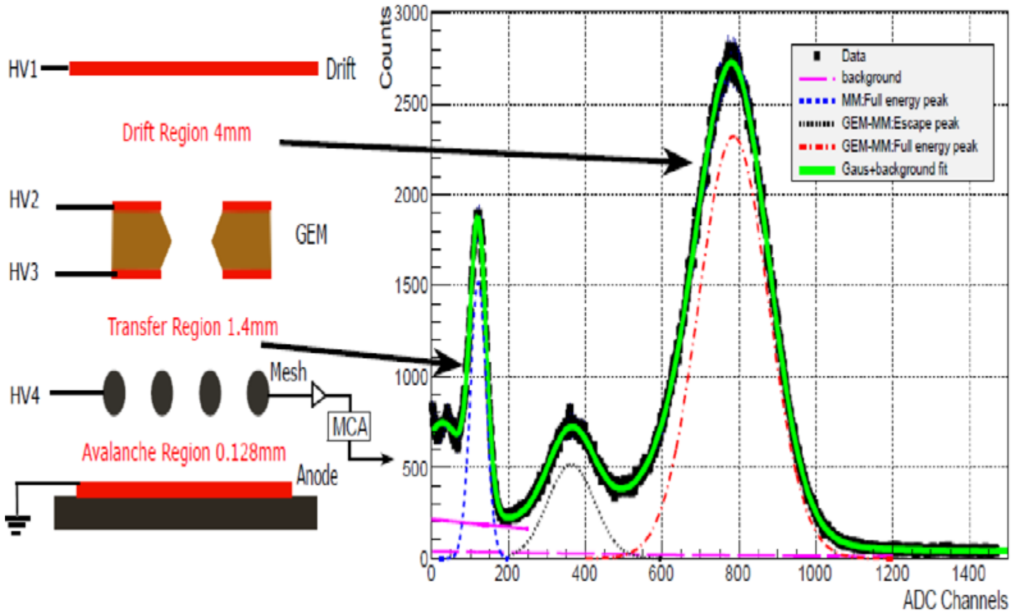


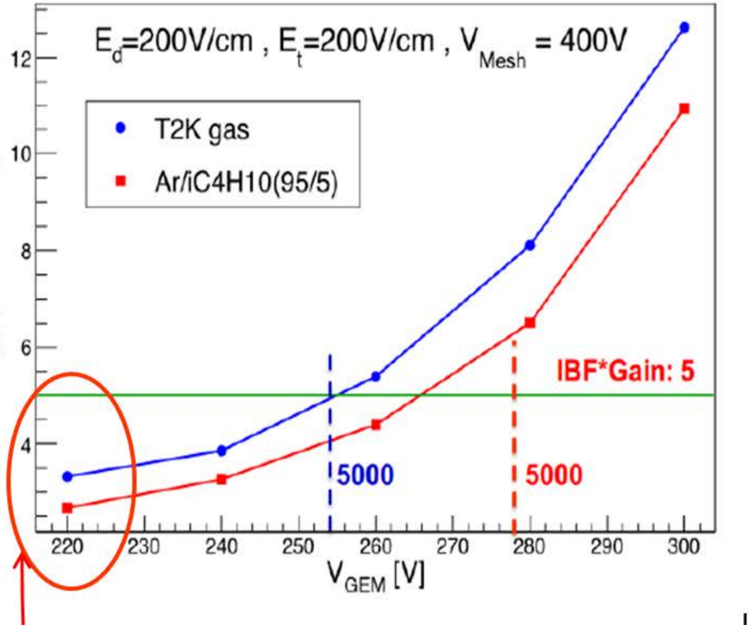
Cite#1 Occupancy in the CLIC
Cite#2 https://doi.org/10.1088/1748-0221/12/07/P07005
Cite#3 GridPix detectors

Ion back flow R&D and results

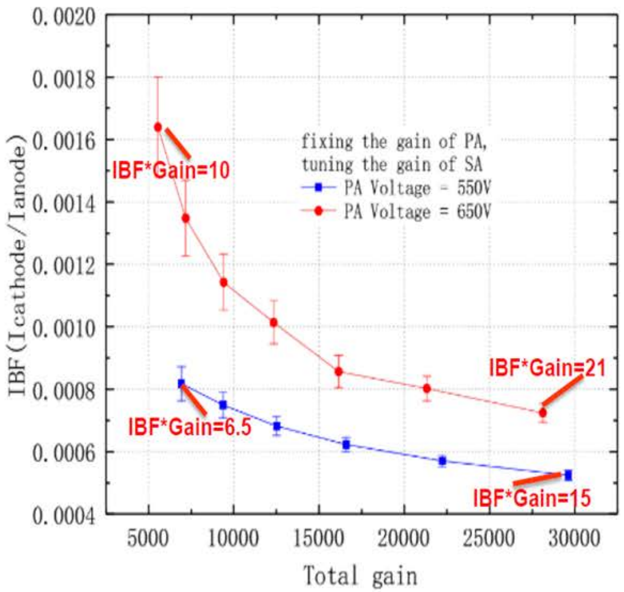
- Achievement by far from TPC module and prototype:
  - Supression ions hybrid TPC module
    - **IBF×Gain ~1 at Gain=2000 validation** with TPC module
  - Spatial resolution of $\sigma_{r\varphi} \leq 100\ \mu m$ by TPC prototype
  - dE/dx for PID: <3.6% (as expected for CEPC baseline detector concept)
  - Graphene foil suppression (on going @ Shangdong University)







IBF of double mesh MM @USTC/Jianbei Liu



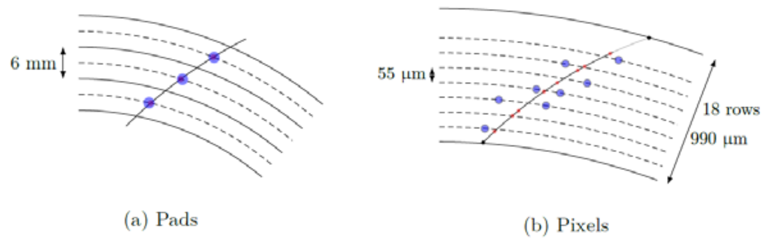
Cite#4: DOI:10.1016/j.nima.2020.164282
Cite#5: CERN-OPEN-2021-012. 2021
Cite#6: IJMPA 36.22 (20212142015

Hybrid TPC module and Double-mesh detector module

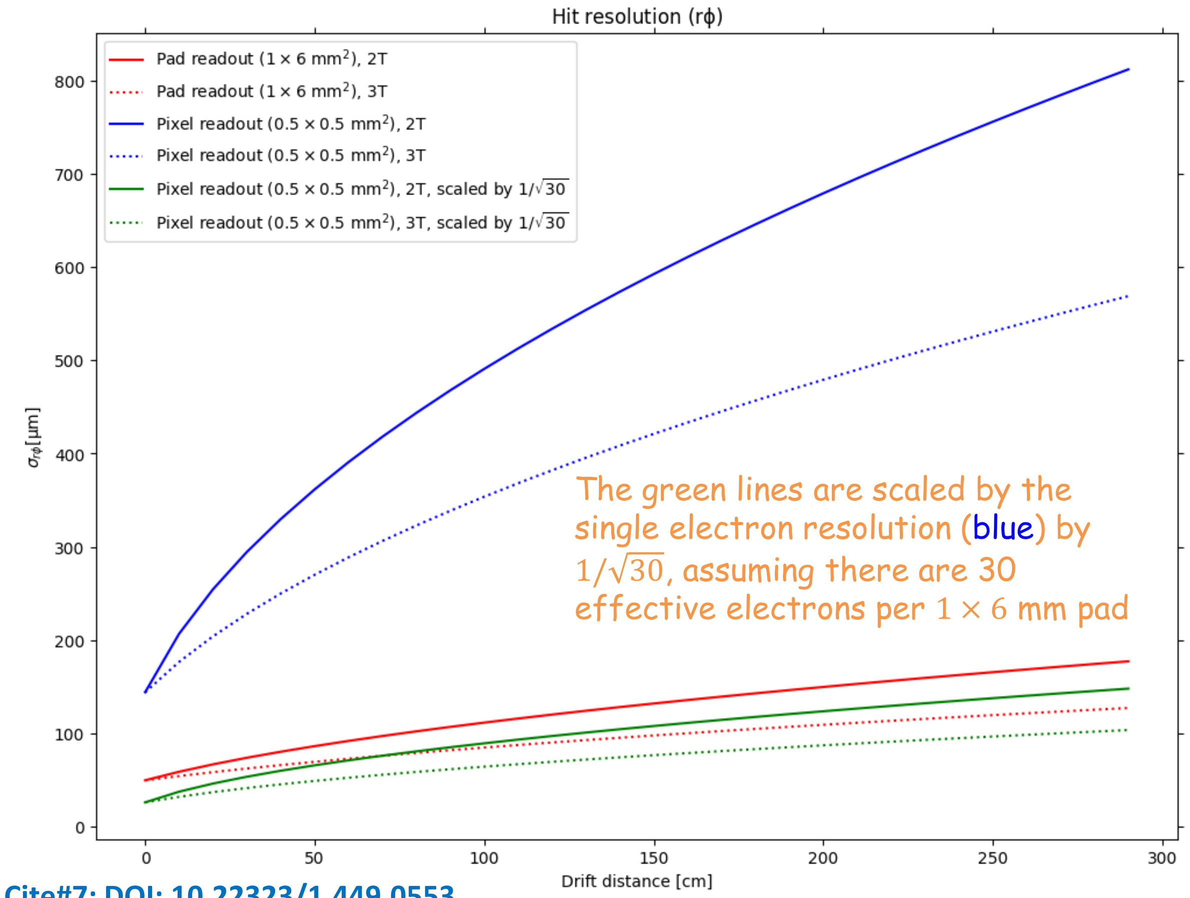
Tera-Z at 2T R&D and results

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 (Backup slide)



(a) Pads (b) Pixels



Pad readout:

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

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

Pixel readout:

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

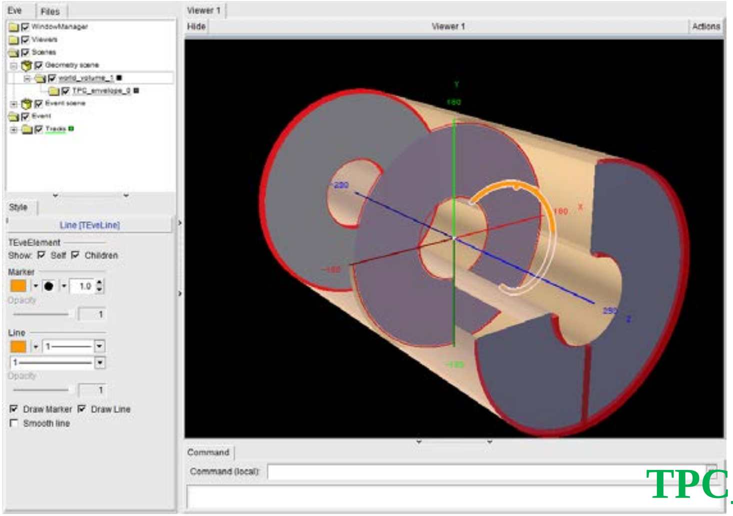
- $\sigma_{r\phi 0} = \frac{500}{\sqrt{12}} = 144\mu\text{m}$
- $D_{r\phi} = 46.9\mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3\mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

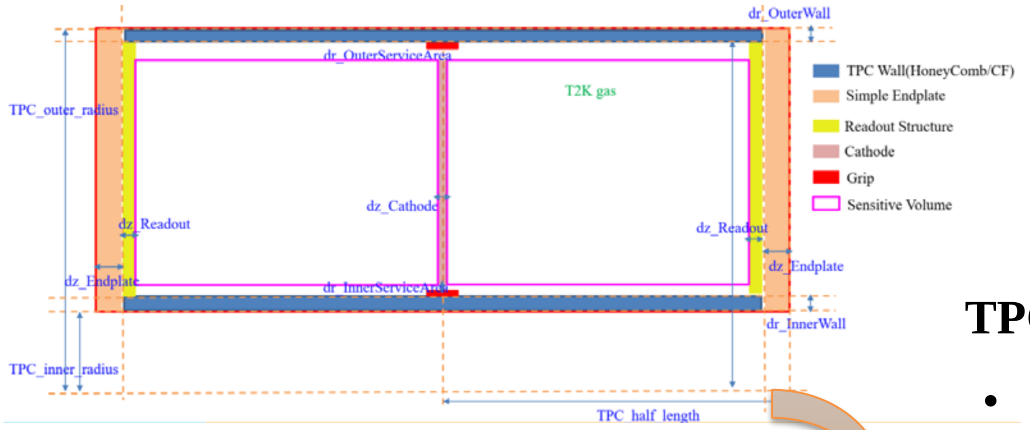
Cite#7: DOI: 10.22323/1.449.0553

Update TPC parameters to CEPCSW software package

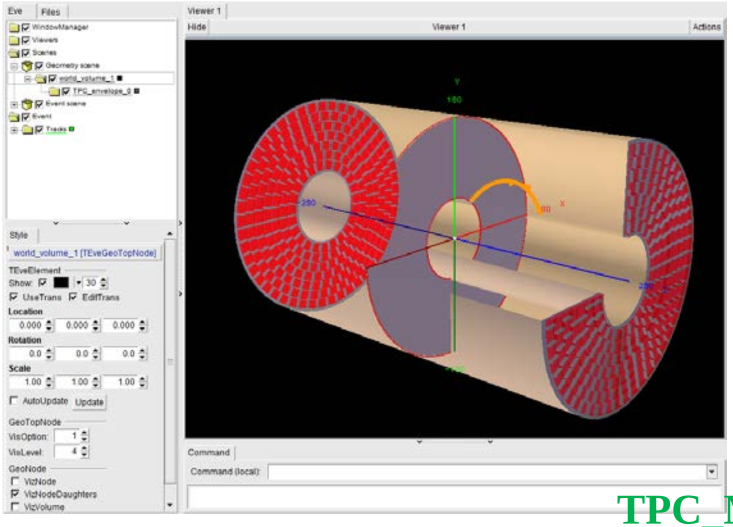
- All parameters of TPC detector **completed** to input CEPCSW software package.
  - Based on the update geometry of TPC as the track detector in CEPC TDR

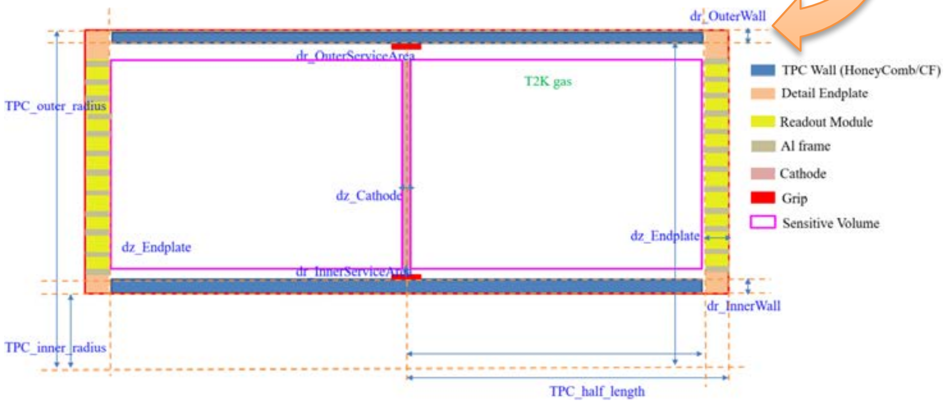
Xin She





TPC_Simple_TDR_o1-v01





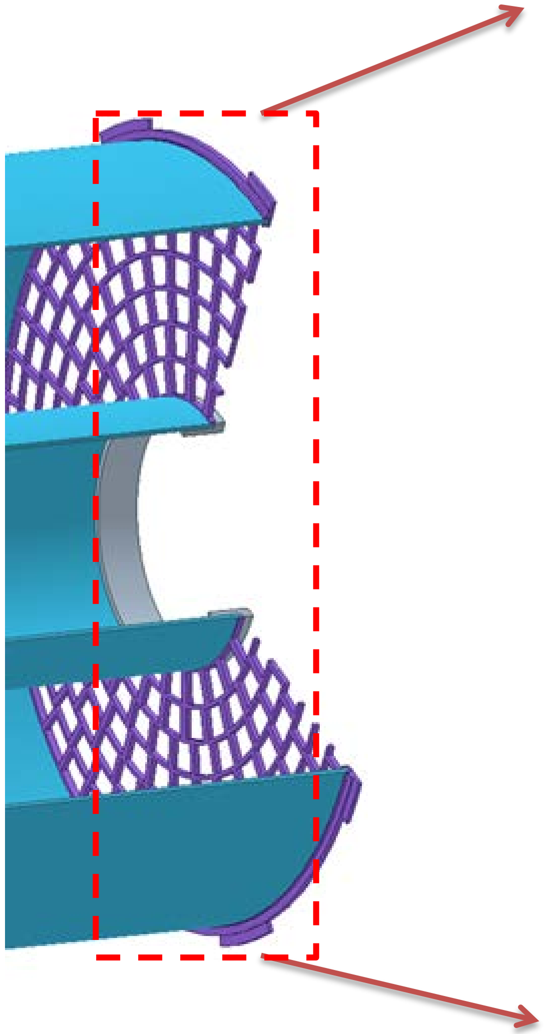
TPC_ModularEndcap_TDR_o1-v01

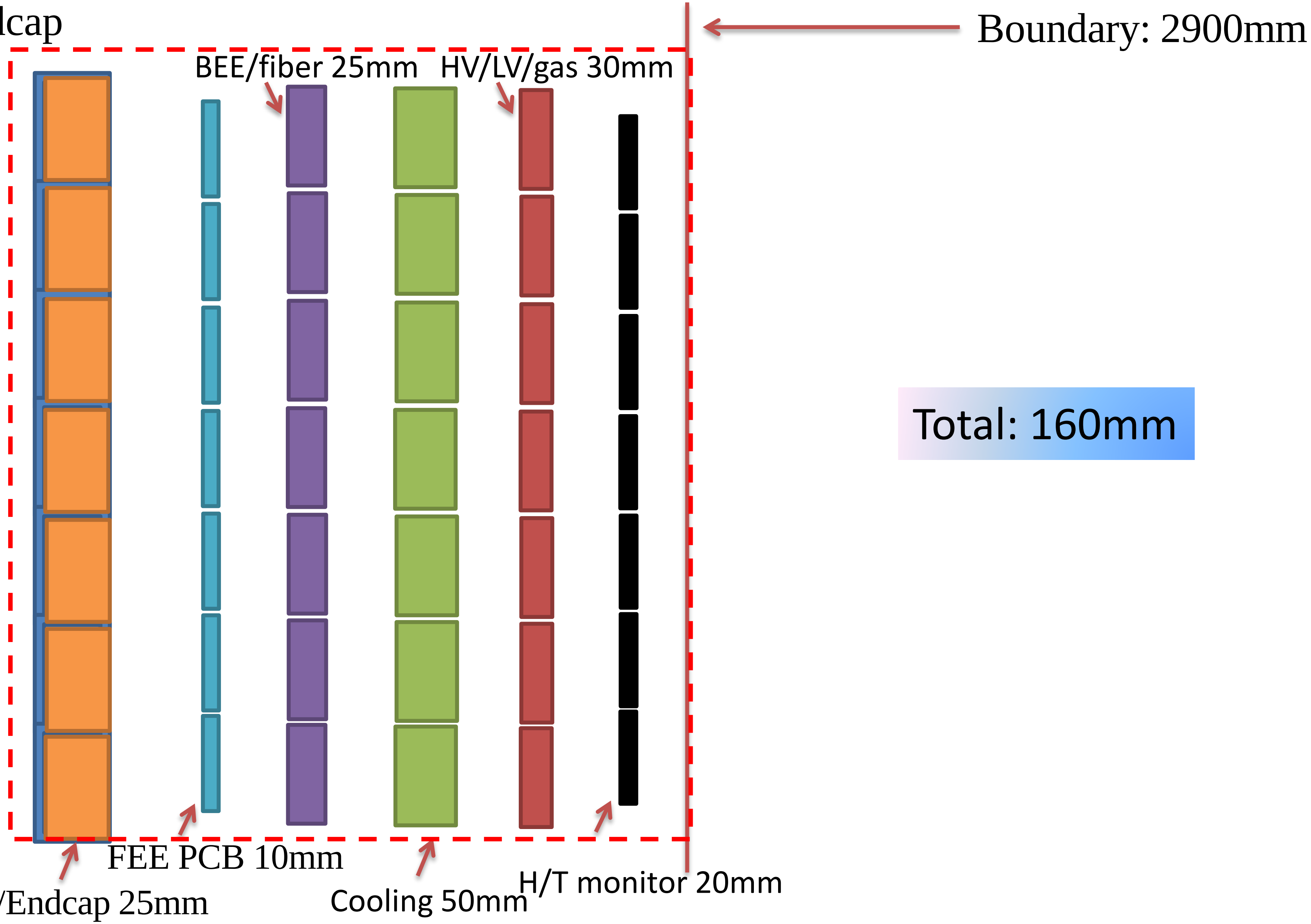
TPC parameters updated to CEPCSW

- Gas Volume: T2K mixture gases
- MPGD Readout: Micromegas detector
- Barrel: Honey comb and CF options
- Endplate: optimization to the details design
- Mechanics: update geometry

Geometry of Endcap

- Geometry of TPC Endcap





Total: 160mm

Updated material budget of TPC barrel and endcap

- **Low material of the TPC endcap**

  15%X_0 in total, including

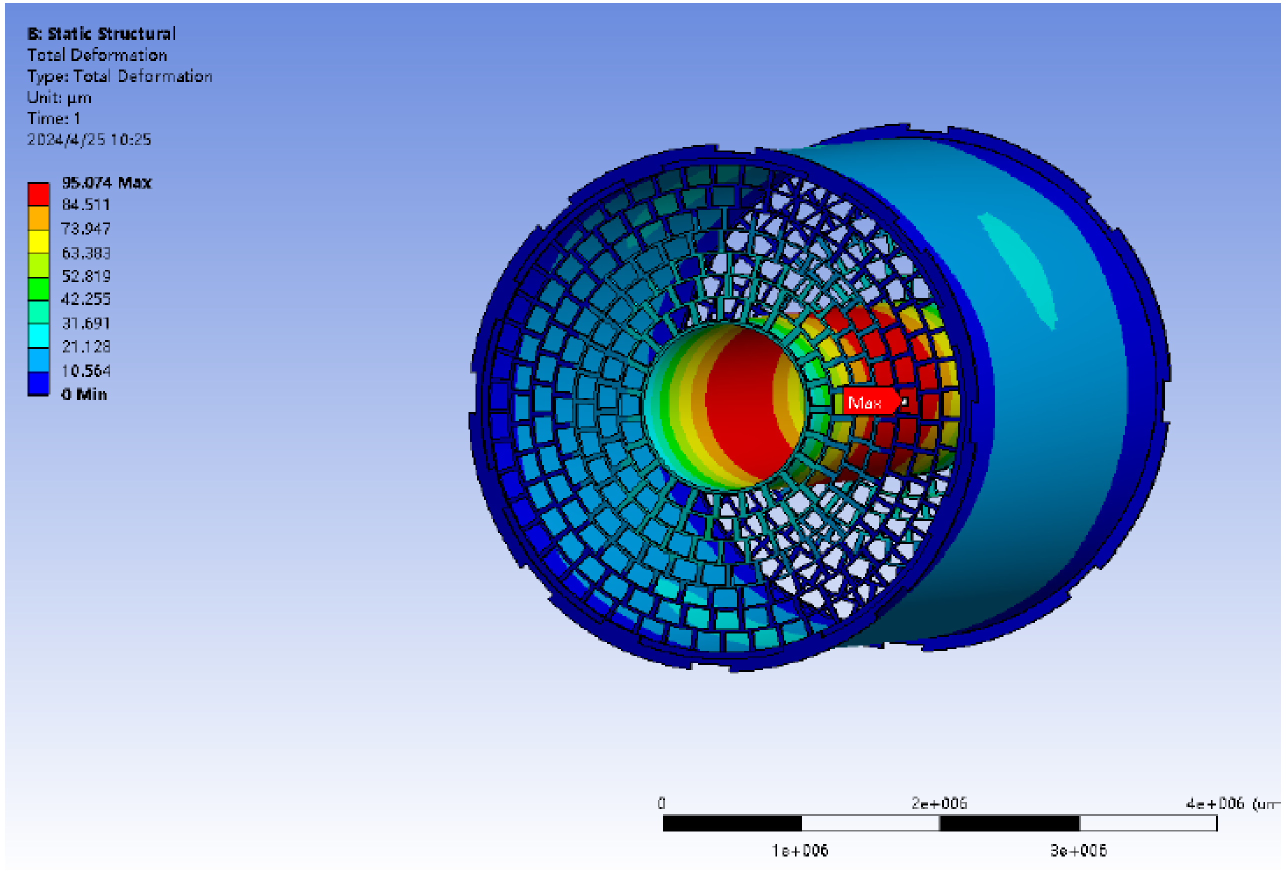
Readout plane, front-end-electronics	4%
Cooling	2%
Power cables	9%

- **Low material of the TPC barrel**

  0.59% X_0 in total, including

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**

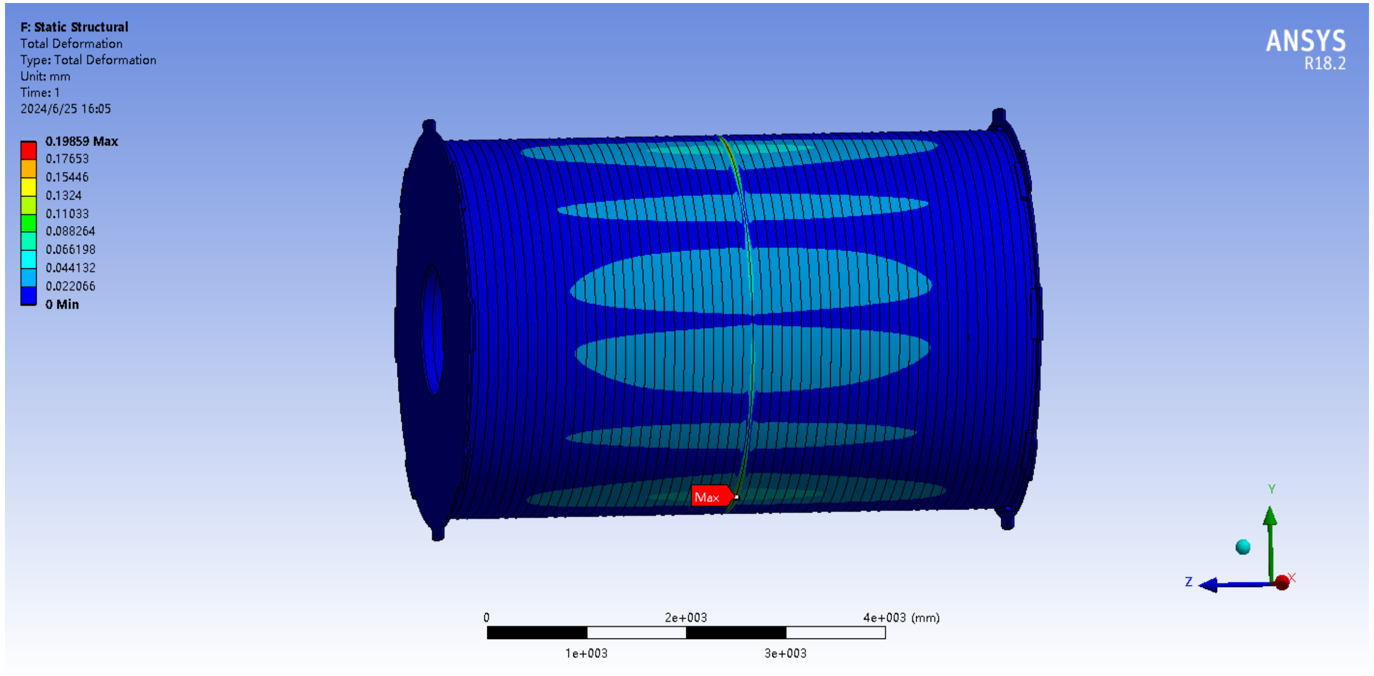


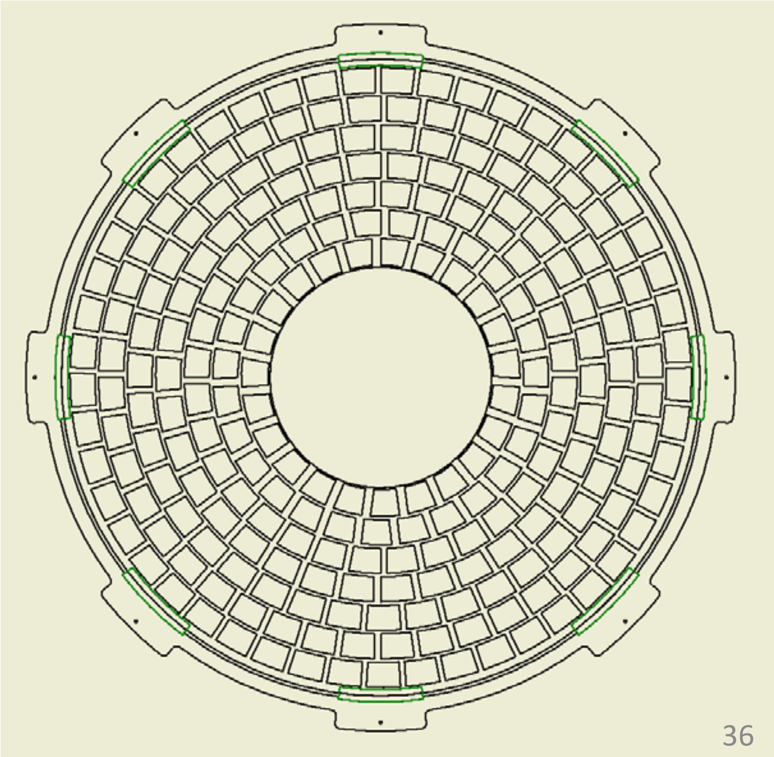
FEA analysis results of TPC

Ultra-light material of the TPC barrel

High-strength carbon fiber material QM55

For thin-walled structures, the shear stresses (剪切应力) from deformations of 0.1mm may occur that exceed the shear stress of the carbon fiber to lead a risk of fracture.



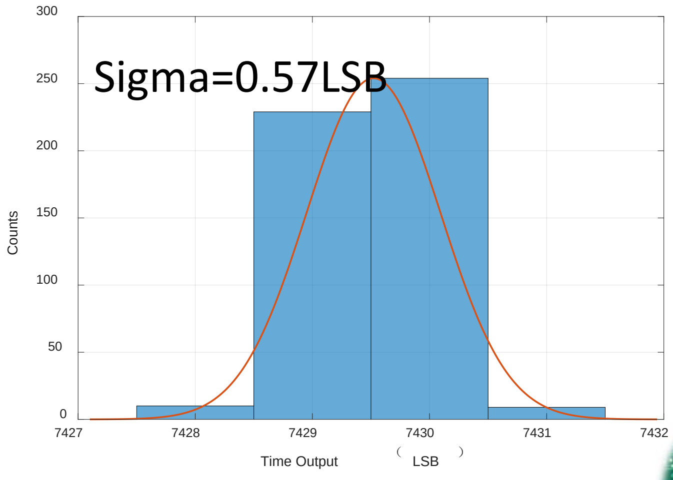


Detailed design of electronics and BEC

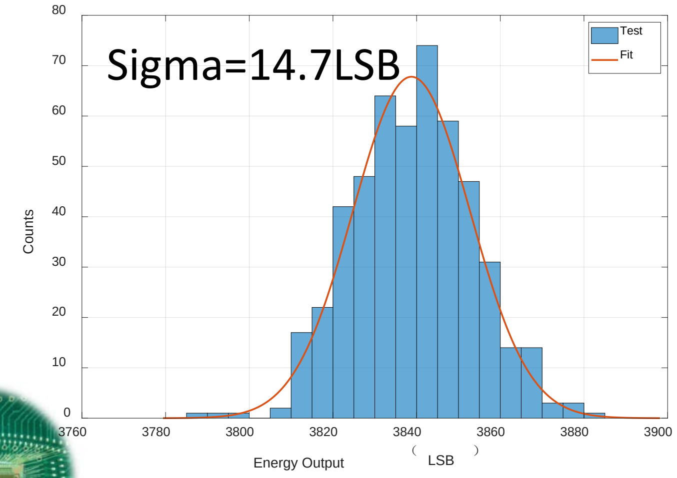
FEE ASIC: TEPIX—Test Results in May

- Power Consumption ~ 0.5mW/ch
- Timing ~ <1LSB(10ns)
- Noise ~ < 300e (even high gain)

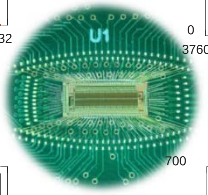
Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns

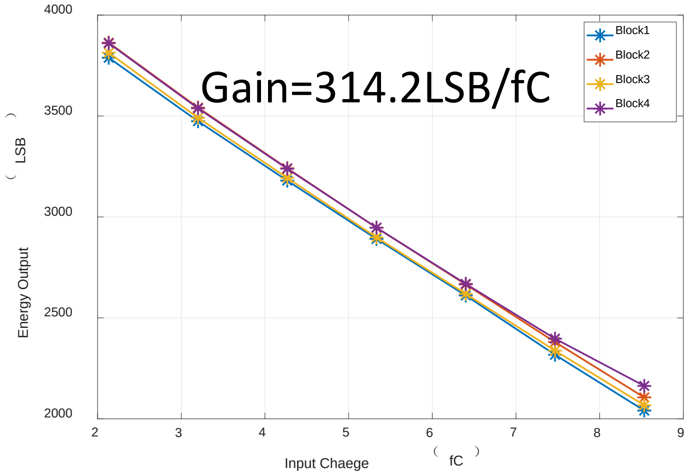


Timing Results

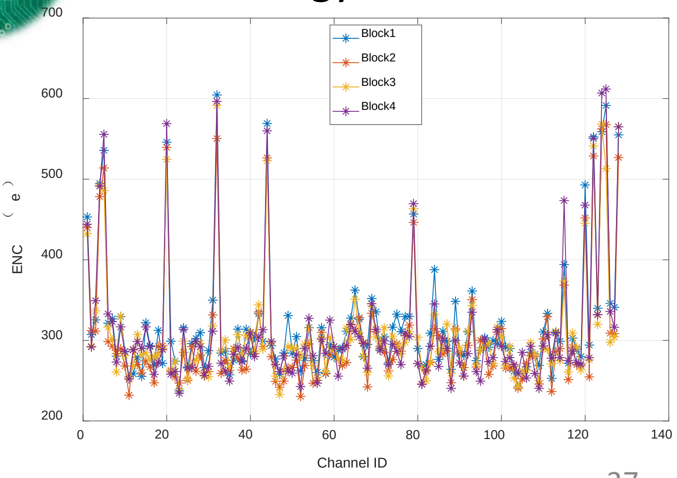


Energy Results





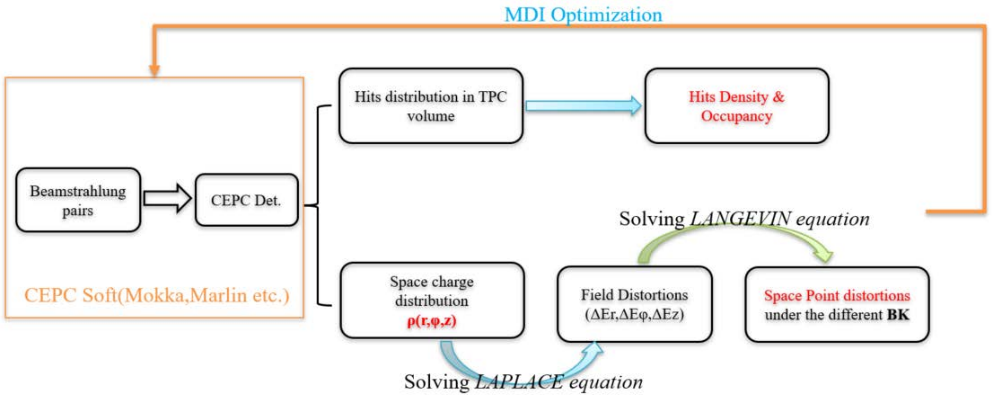
Gain



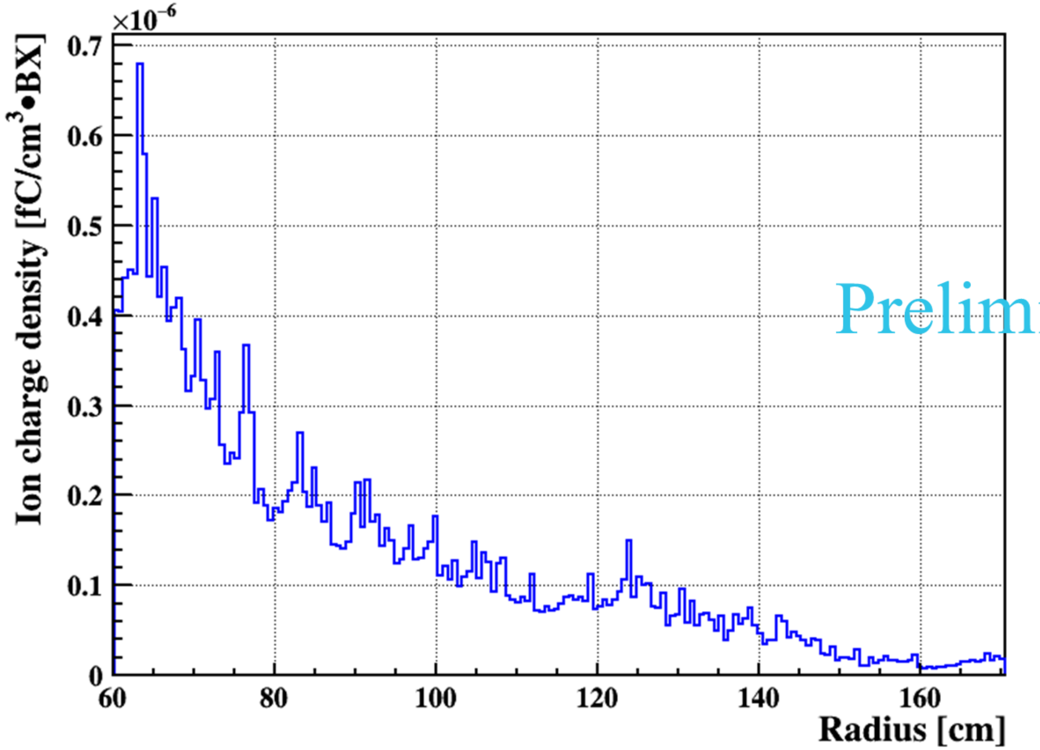
Noise

Updated of the hits density & occupancy at Tera-Z with BK

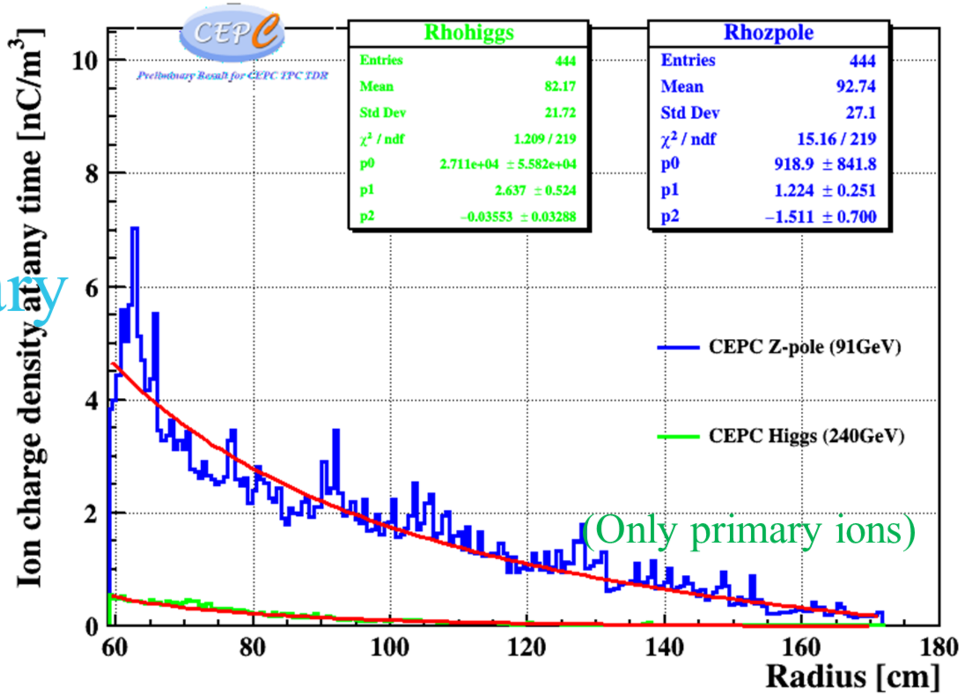
- **Updated simulation results from CEPCSW**
  - Single BX , ρ_{sc}(single BX)~ 0.6e-6 nC/m^3/BX @Z-pole
  - ρ_{sc}(steady state)~ ρ_{sc}(single BX) × BX freq. × max. drift time × 50% × η = 5.46 nC/m^3 (r=60cm) @Z-pole
    - **×5 smaller than FCCee -91**



Ionization efficiency(90%)



Preliminary

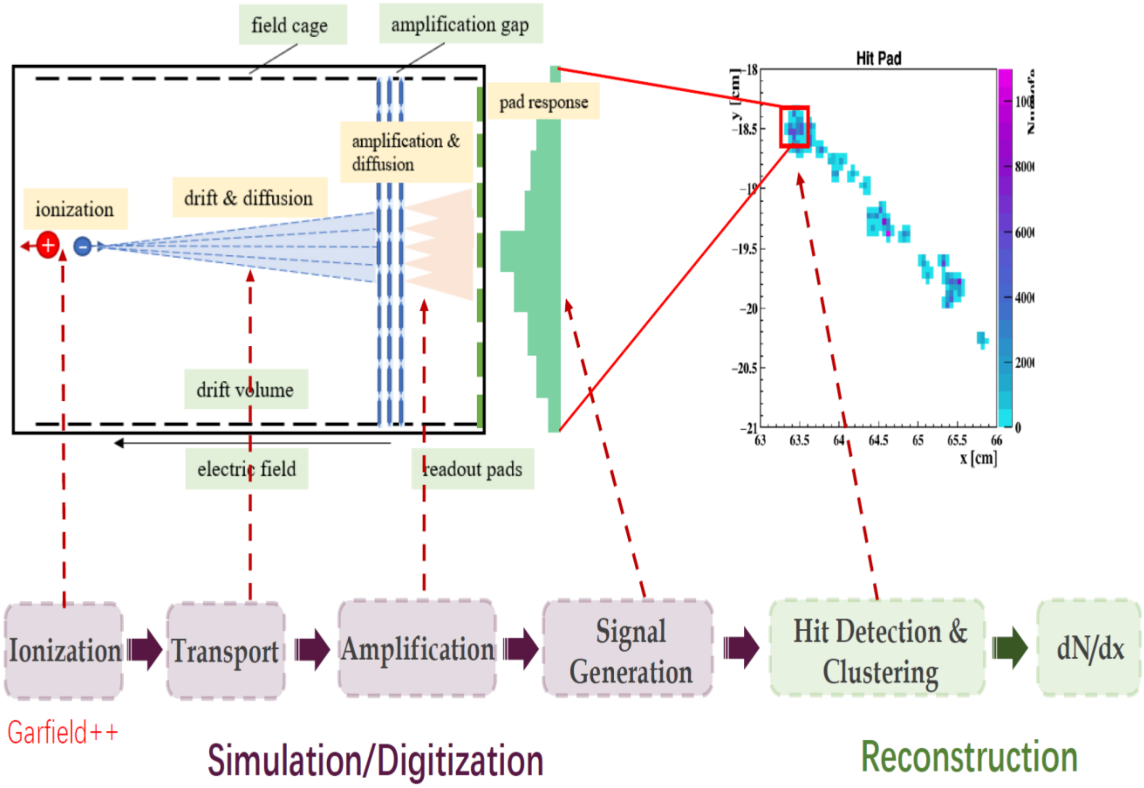


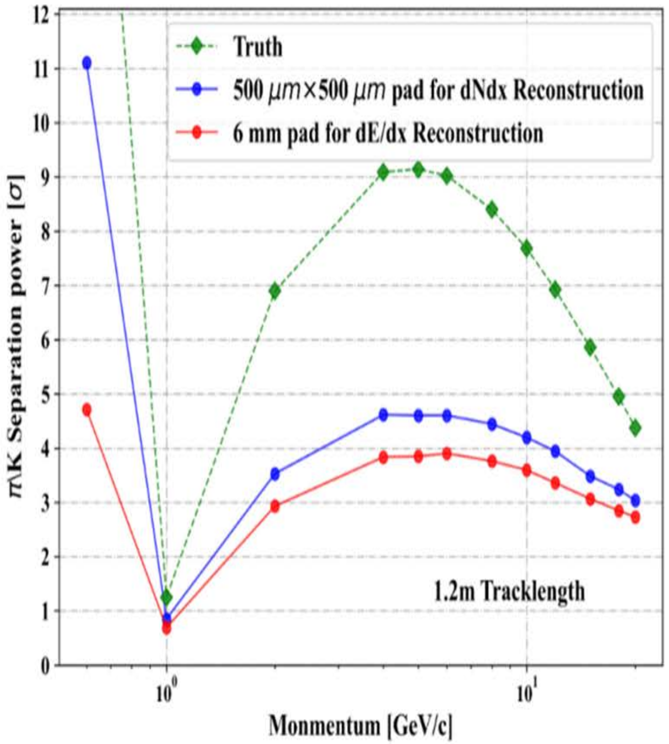
$\rho_{sc}(r)$ (single BX) distribution Left & $\rho_{sc}(r)$ (steady state) Right

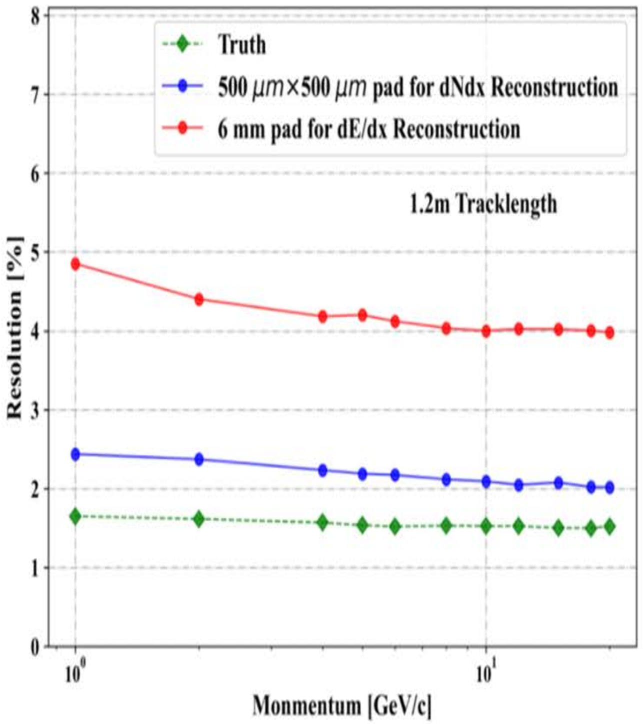
#3. Improved dE/dx+dN/dx √

- 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 50cm drift length can be achieved
- dN/dx has significant potential for **improving PID resolution**

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







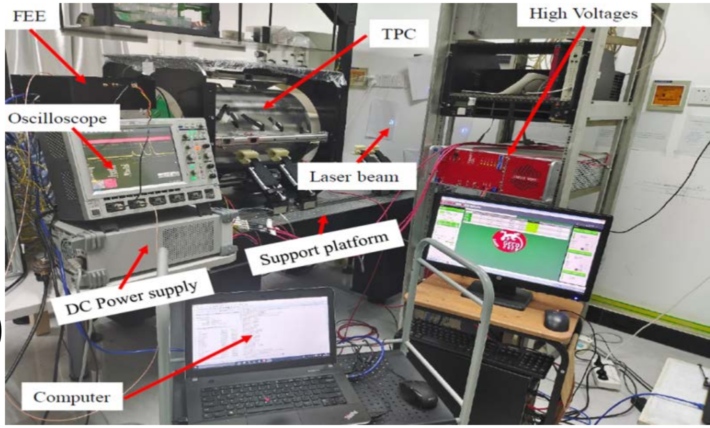
Cite#5 DOI: 10.22323/1.449.0553

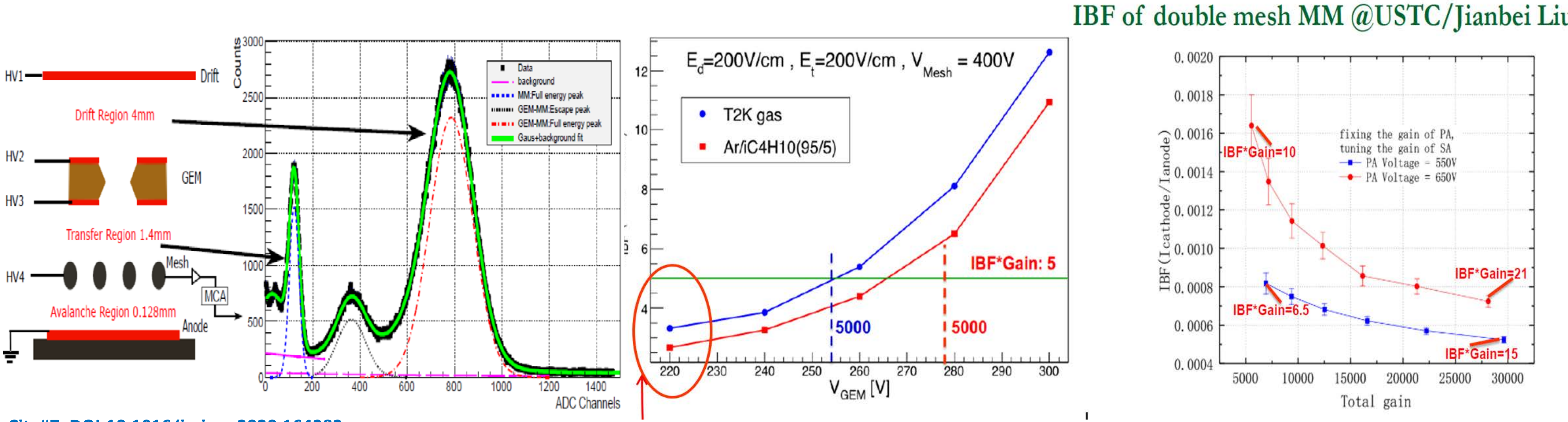
Cite#6 EPS-HEP 2023 talk by Yue Chang

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

#4. Ion backflow suppression √

- Achievement by far from TPC module and prototype:
  - Supression ions hybrid TPC module
    - **IBF×Gain ~1 at Gain=2000 validation** with TPC module
  - Spatial resolution of **$\sigma_{r\varphi} \leq 100$ μm** by TPC prototype
  - dE/dx for PID: <3.6% (as expected for CEPC baseline detector concept)
  - Graphene foil suppression (on going @ Shangdong University)



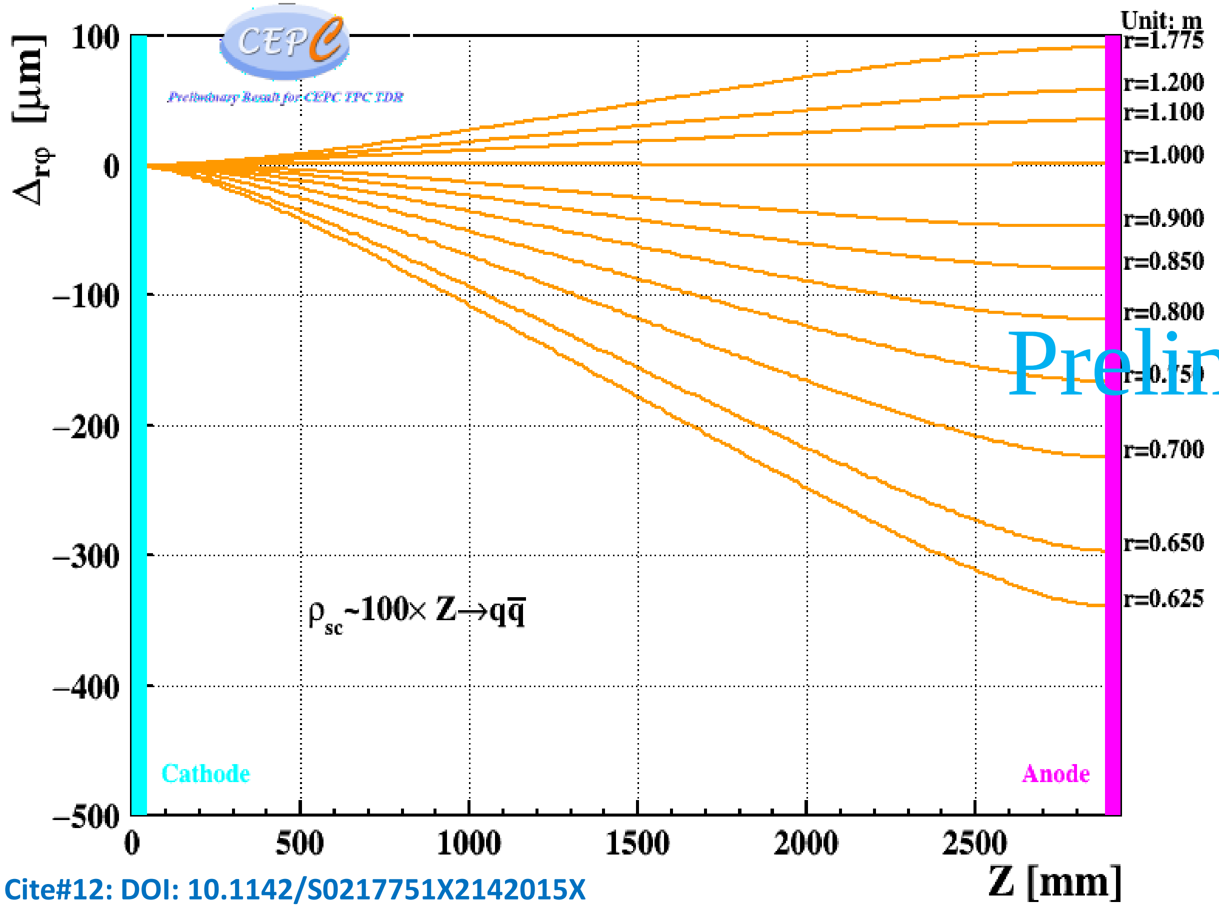


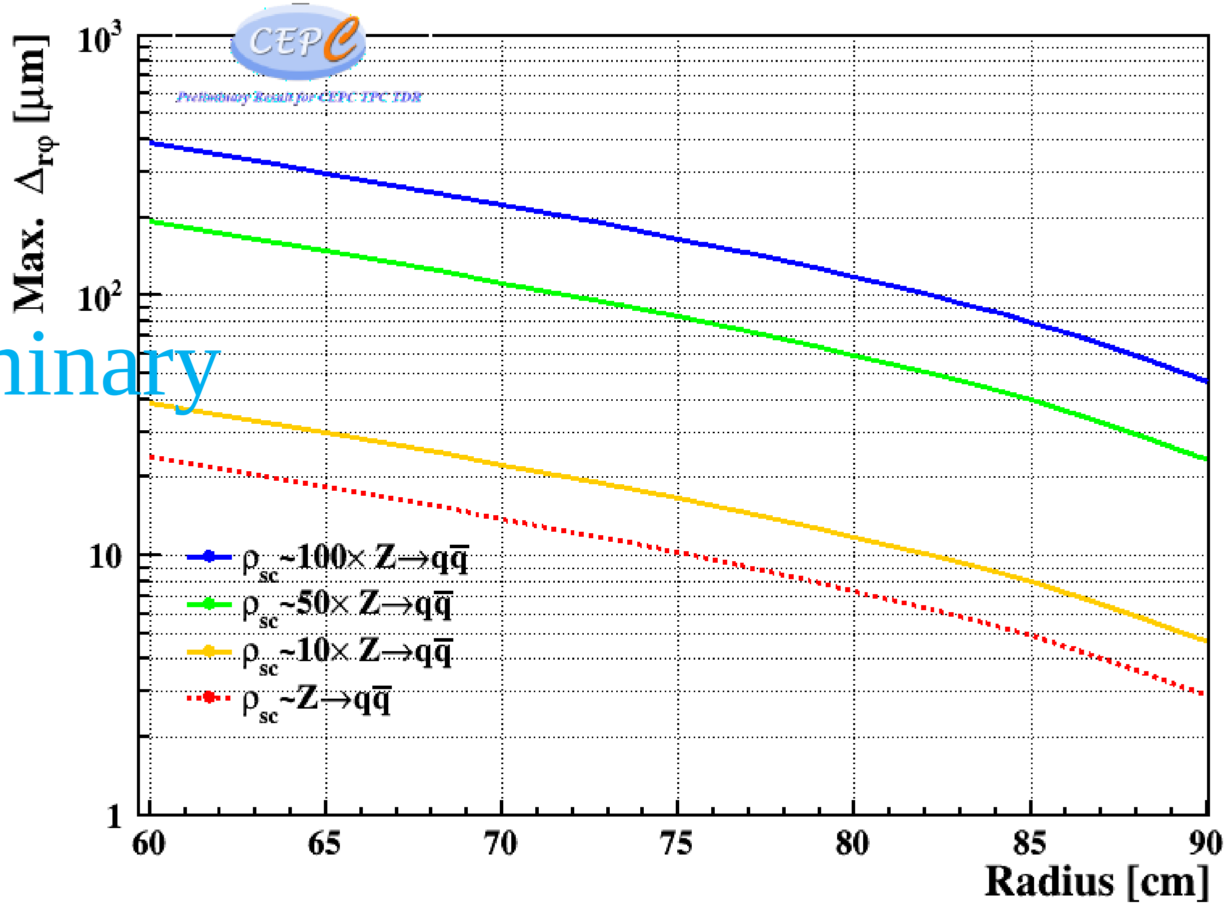
Cite#7: DOI:10.1016/j.nima.2020.164282
Cite#8: CERN-OPEN-2021-012. 2021
Cite#9: IJMPA 36.22 (20212142015

Hybrid TPC module and Double-mesh detector module

#7. Beamstrahlung and distortion √

- Maximum distortion with e+e- to qq at Z pole (Physics events only)
- Maximum distortion under the different Beamstrahlung background (×10, ×50 , ×100 times Physics events)
  - MDI design at Z need carefully optimized with MDI group in CEPC



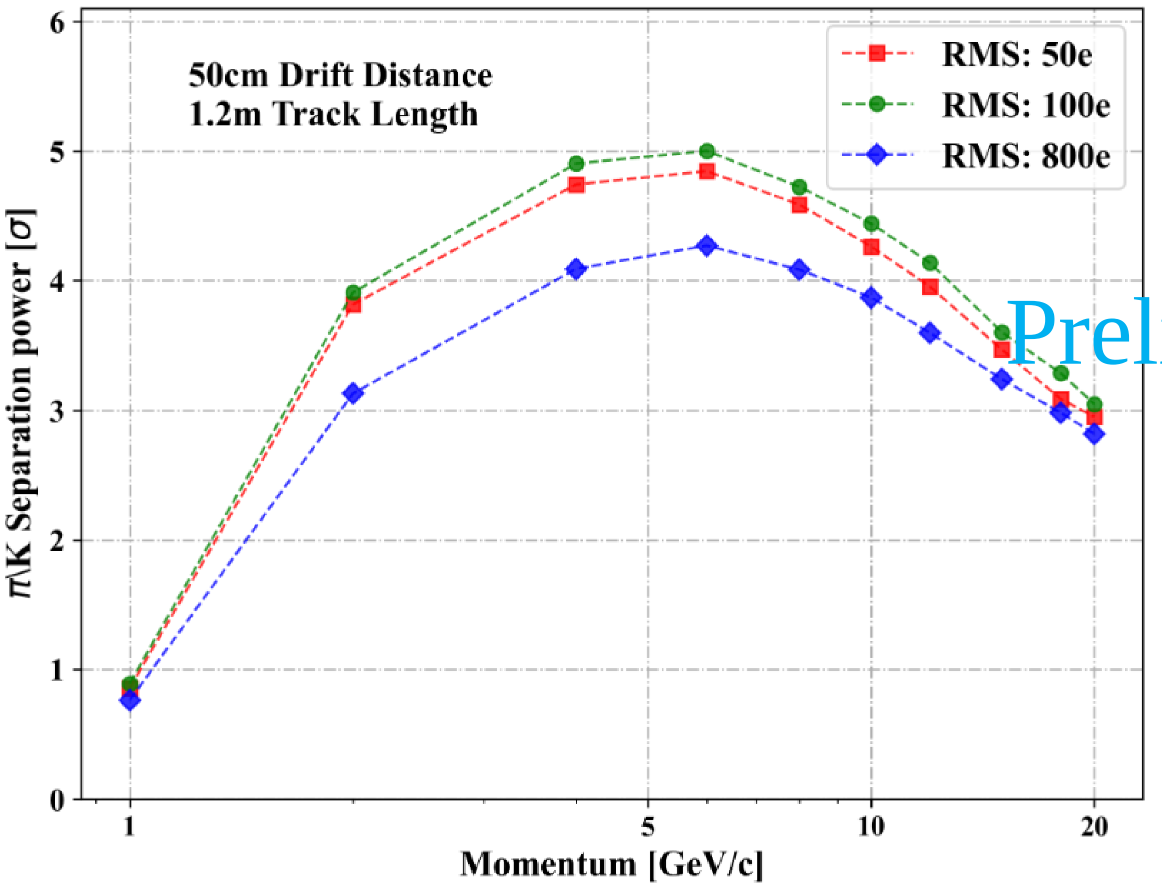


Cite#12: DOI: 10.1142/S0217751X2142015X
Cite#13: DOI: 10.1016/j.nima.2022.167241
Cite#14: DOI: 10.1088/1748-0221/12/07/P07005

Noise of FEE VS Separation power

Estimation of the **FEE readout** using Micromegas.

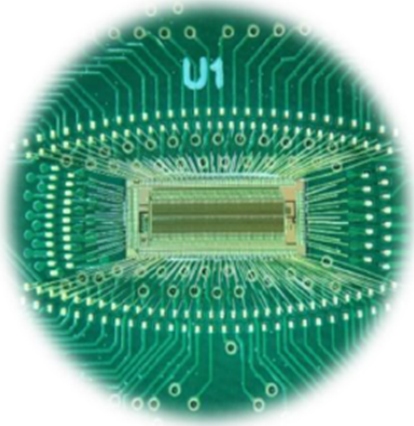
- The noise of the FEE should be kept the lower to keep the reasonable gain of the detector (-2000).
- The noise of the FEE reached to 100e.



R&D on Pixelated TPC readout for CEPC TDR

- Macro-Pixel TPC ASIC chip was started to developed and **2nd prototype wafer has done** and tested
- The **TOA and TOT** can be selected as the initiatic function in the ASIC chip
  - 500μm×500μm pixel readout designed
  - Noise of FEE: ~100e
  - Time resolution: **14bit** (5ns bin)
  - **Power consumption: <1mW/pixel (2nd prototype**
    - **~100mW/cm²**

Preliminary



Pad size optimization

- Pad size optimization ongoing.
    - Optimized the pad size to validate the PID performance

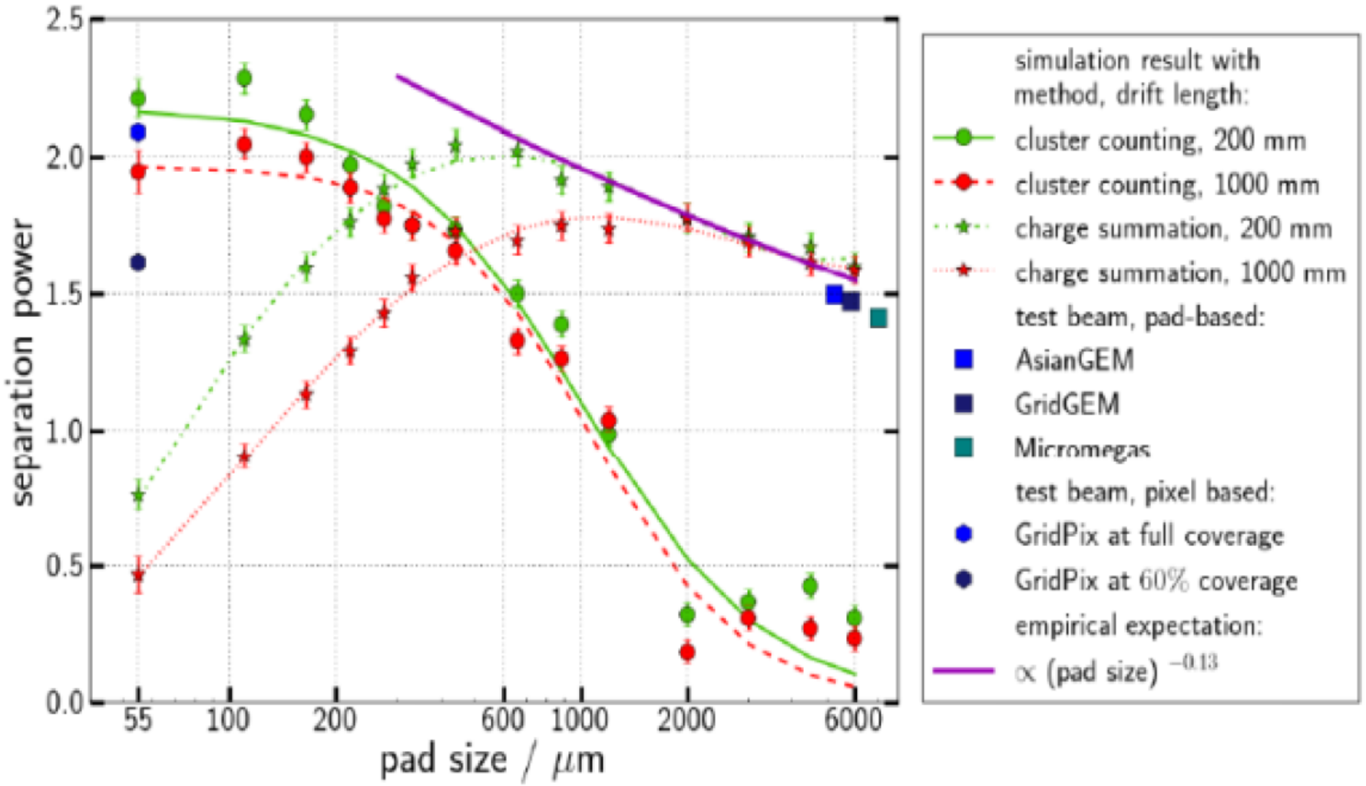
- **dN/dx (and tracking) can be beneficial from smaller pad size**

$$\rho_{cl} \approx 30cm^{-1} \Rightarrow Pad\ size \approx 300\mu m$$

(To detect single e^-)

- **Need to find out the optimal pad size considering cost/power consumption**

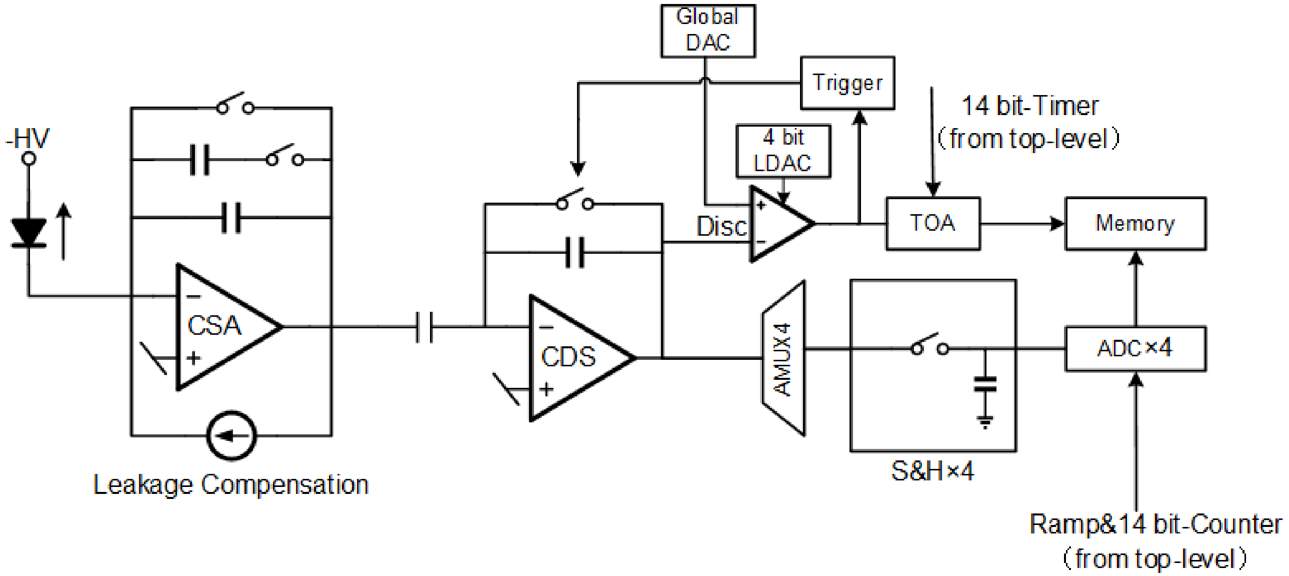
Simulation with 30 cm track length

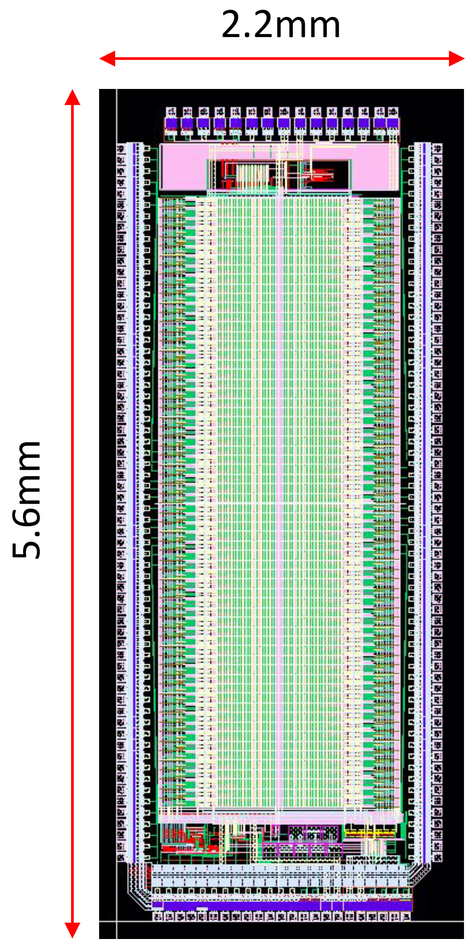


https://doi.org/10.1088/1748-0221/17/11/P11027

Detailed design of electronics and BEC

- FEE ASIC: TEPIX
  - Charge Sensitive Preamplifier(CSA)
  - CDS amplifier provides additional gain and noise shaping
  - Wilkinson type ADC each pixel
  - Timing discriminator with Time of Arrival information

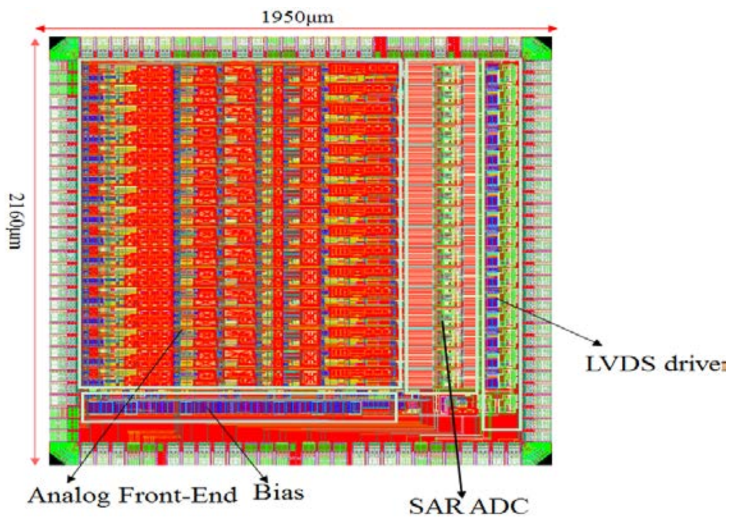




Detailed design of electronics and BEC

- 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**

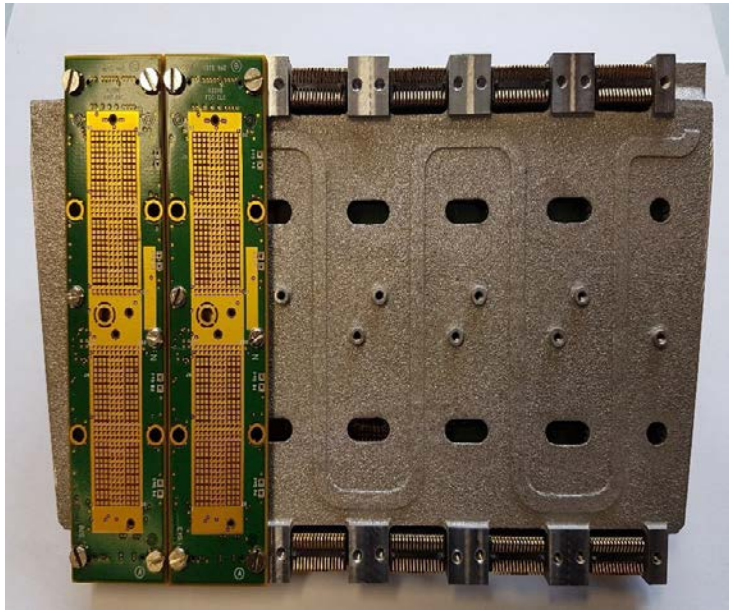
	PASA+ALTRO	Super-ALTRO	SAMPA	WASA_v1
TPC	ALICE	ILC	ALICE upgrade	CEPC
Pad Size	4x7.5 mm^2	1x6 mm^2	4x7.5 mm^2	1x6 mm^2
No. of Channels	5.7× 10^5	1-2 × 10^6	5.7 × 10^5	2 x×10^6
Readout Detector	MWPC	GEM/MicroMegas	GEM	GEM/MicroMegas
Gain	12 mV/fC	12-27 mV/fC	20/30 mV/fC	10-40 mV/fC
Shaper	CR-(RC)^4	CR-(RC)^4	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

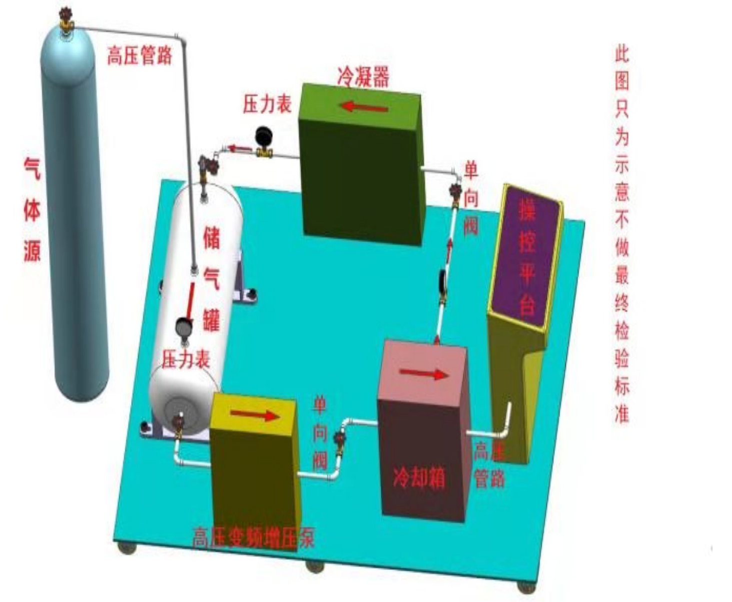


DOI: 10.1088/1748-0221/15/02/T02001
DOI: 10.1088/1748-0221/15/05/P05005

Detailed design of mechanic and cooling

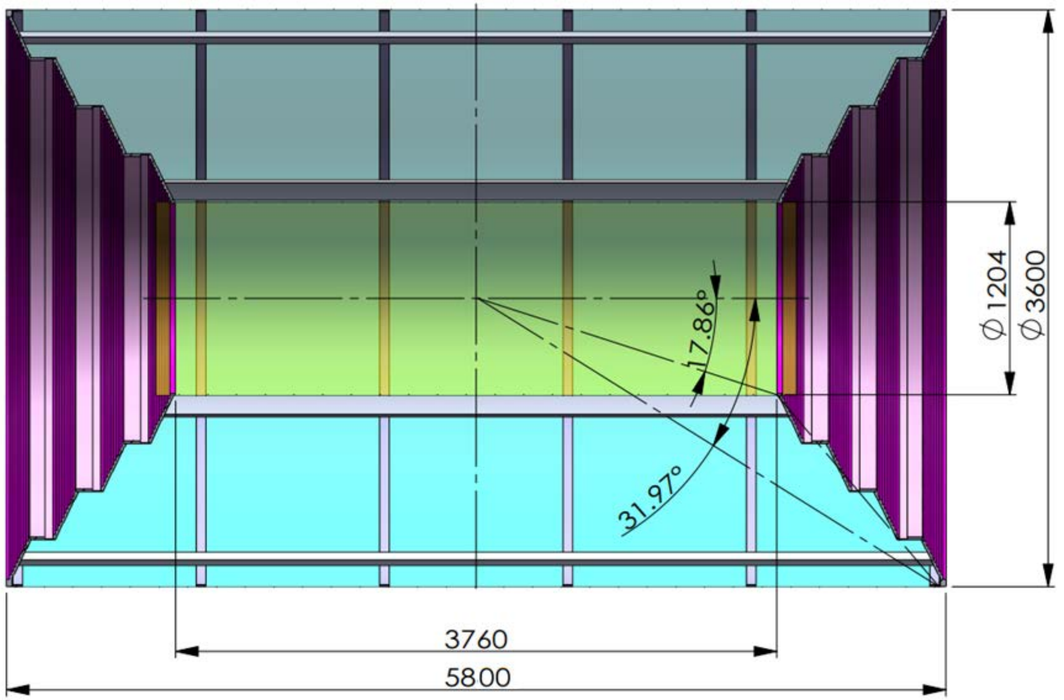
- Readout electronics will require a cooling system. **2-phase CO2-cooling** is a very interesting candidate.
  - A fully integrated AFTER-based solution tested on 7 Micromegas modules during a test beam.
- To optimize the cooling performance and the material budget **3D-printing of aluminum** is an attractive possibility for producing the complex structures required.
  - A prototype for a full module has been **validated at the international collaboration**.

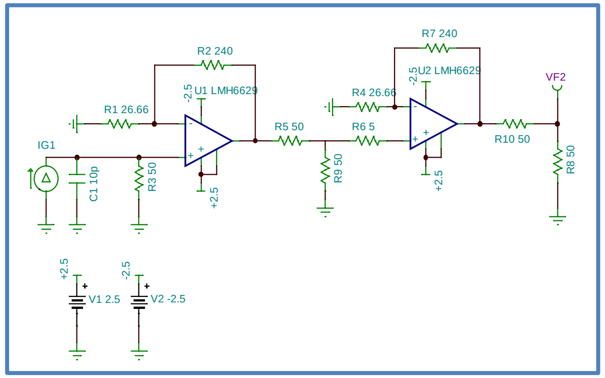


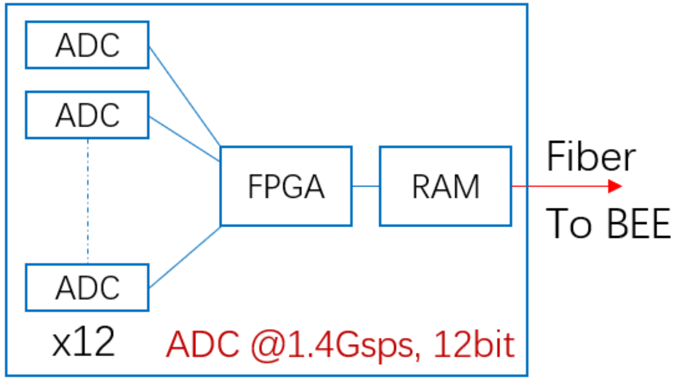


Cite#8: DOI 10.48550/arXiv.1403.7717
Cite#9: DOI 10.1088/1748-0221/10/08/P08001
Cite#10: DOI 10.1088/1742-6596/2374/1/012149

Backup of DC R&D







FEE-1:
Rad-hard analog preamps
100mW/ch -> ~2.6kW in total
1.3kW for each end plate, air cooling
no additional material budget

FEE-2:
ADC and FPGA board for data readout and buffering, located in low dose region
0.5Gbps/12 channels

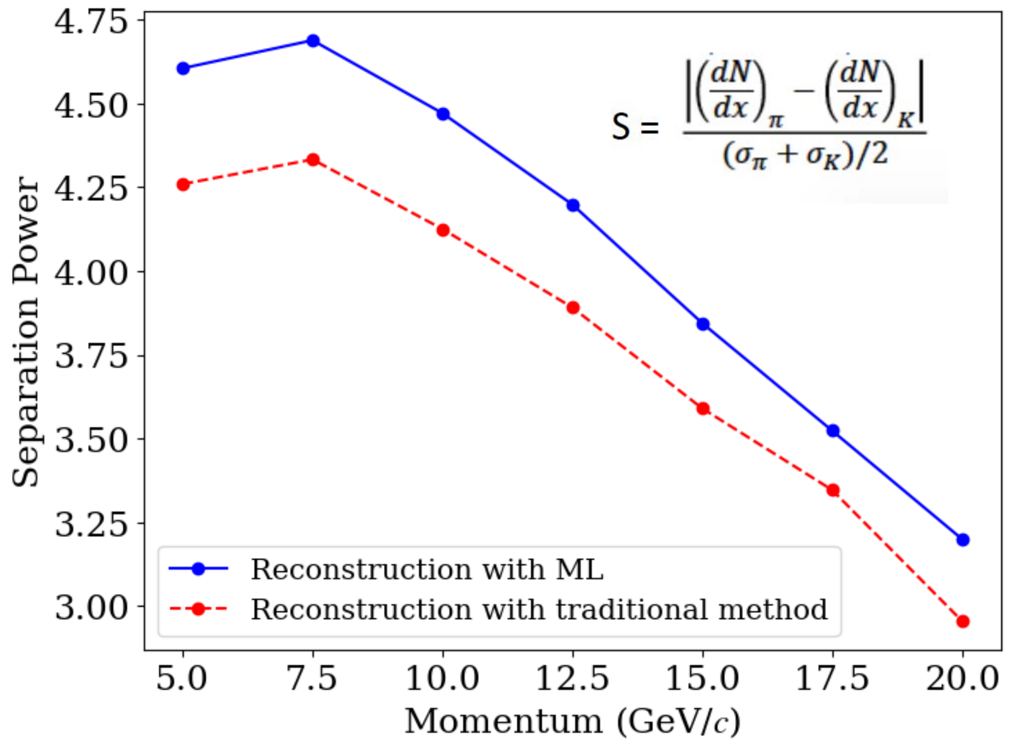
CF frame structure: 8 longitudinal hollow beams + 8 annular hollow beams + inner CF cylinder and outer CF cylinder
Length: 5800 mm; Outer diameter: 3600 mm; Inner diameter: 1200 mm
Thickness of each end plate: 20 mm, weight: 880 kg
Gas mixture: He + iC_4H_{10} (90/10)
Cell size: 18mm x 18mm, number of 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

Full simulation study

- Garfield++ based parameterized simulation implemented
- Parameters of preamplifier and noises from experiment
- Reconstruction with both traditional method and machine learning developed

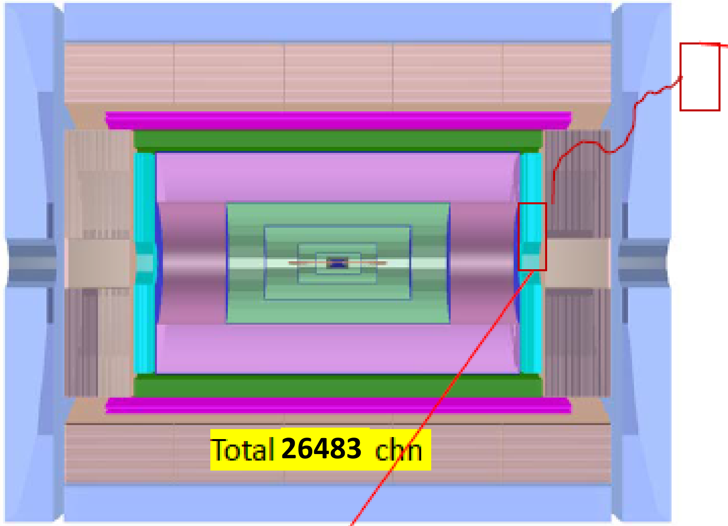
Better than 3σ of K/π separation power achieved up to 20GeV/c

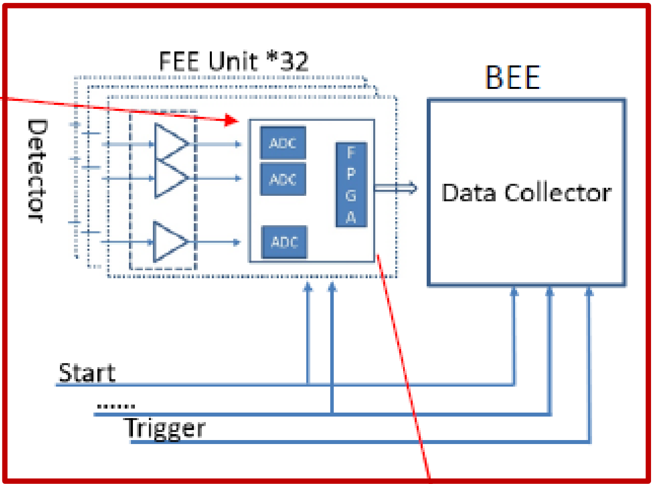
K/π separation power vs. momentum



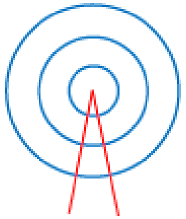
~10% improvement for reconstruction with ML

Detailed design of DC at Tera-Z

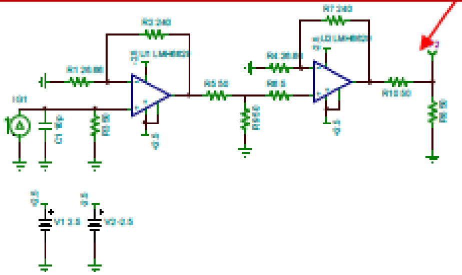




FEE 2: Non-Radiation-hardness FEE with ADC and FPGA



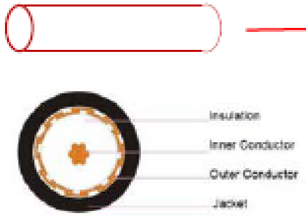
12 chn
Grp by sector



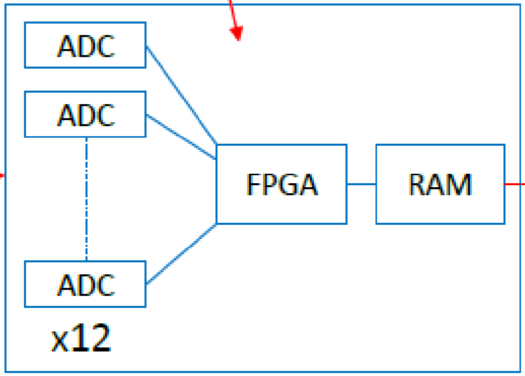
High Bandwidth Preamp
100mW/ch -> 2.7kW in total
1.4kW for each end plate, air cooling is OK
no additional material bufget

FEE 1: Radiation hardness FEE with preamplifier

x12



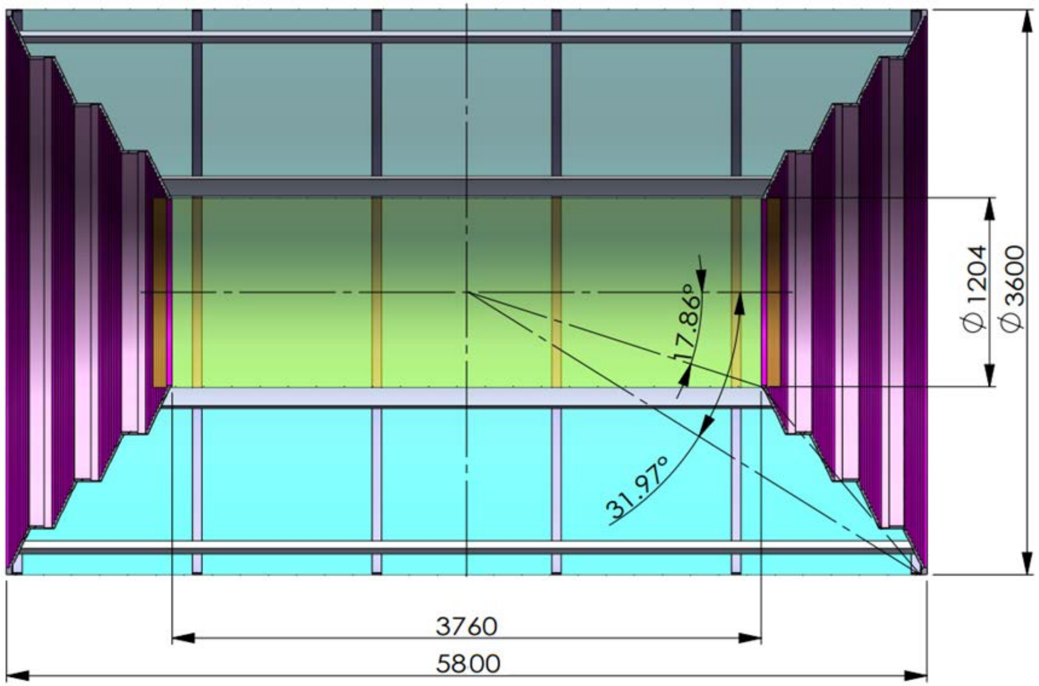
Analog signal on Cable
2.8mm per co-ax
12 signals + 1 Power
3dB attenuation @ 280MHz



Fiber
To BEE

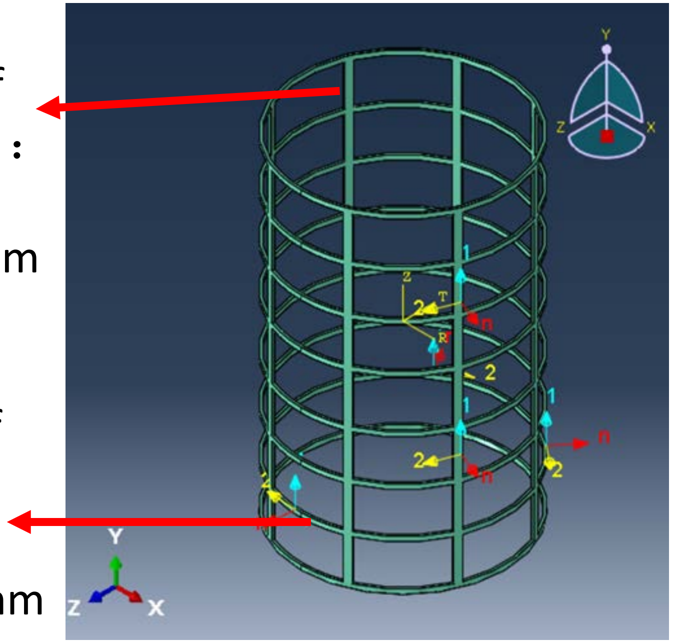
ADC @1.3Gsps, 12bit

Overall mechanical design



Cross section of longitudinal HB：80mm*40mm，thickness: 3.2mm

Cross section of annular HB：40*10mm Thickness: 3.2mm

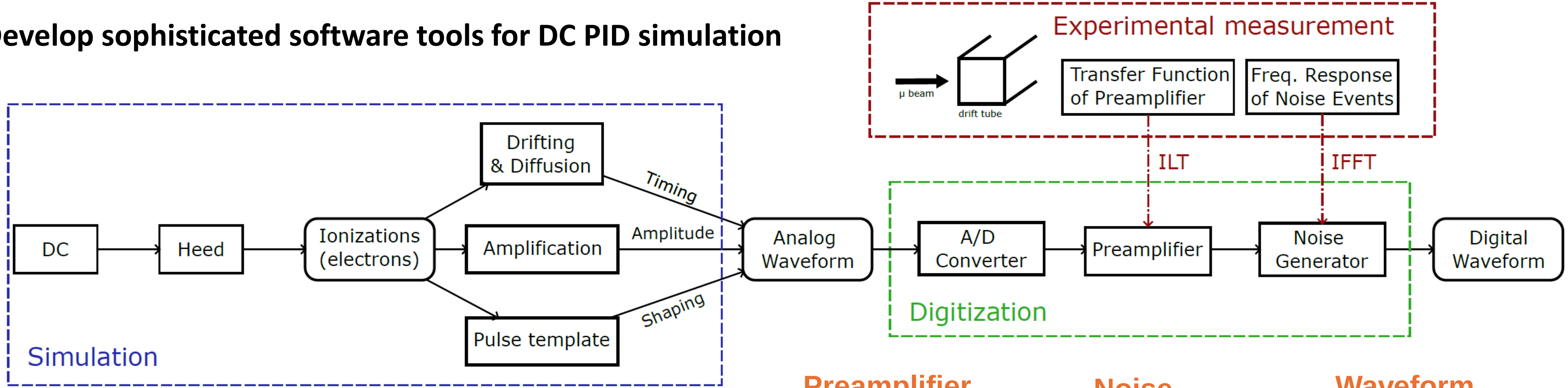


- CF frame structure: 8 longitudinal hollow beams + 8 annular hollow beams + inner CF cylinder and outer CF cylinder
  - Length: 5800 mm
  - Outer diameter: 3600 mm; Inner diameter: 1200 mm
  - Thickness of each end plate: 20 mm, weight: 880 kg

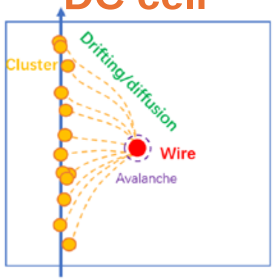
- Finite element analysis
  - Max Mises stress of End plate : 30MPa
  - Endplate deformation 2.7mm
  - Max Mises stress of CF frame : 235MPa
  - CF frame deformation 1.1mm

Waveform-based full simulation

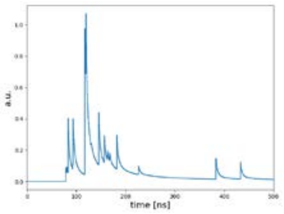
Develop sophisticated software tools for DC PID simulation



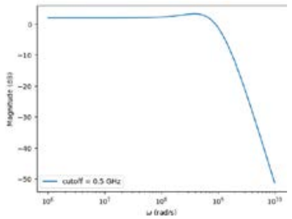
DC cell



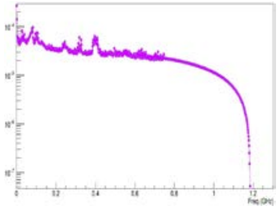
Induced signal



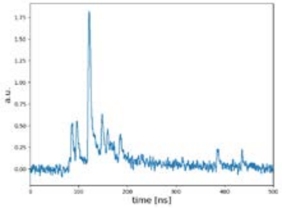
Preamplifier



Noise



Waveform



Tuned MC is comparable to data