CEPC Gaseous Track Detector

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- **Motivation and physics requirements**
- **Technology survey and our choices**
- **Technical challenges and R&D efforts**
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- **Research team and working plan**
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Motivation

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

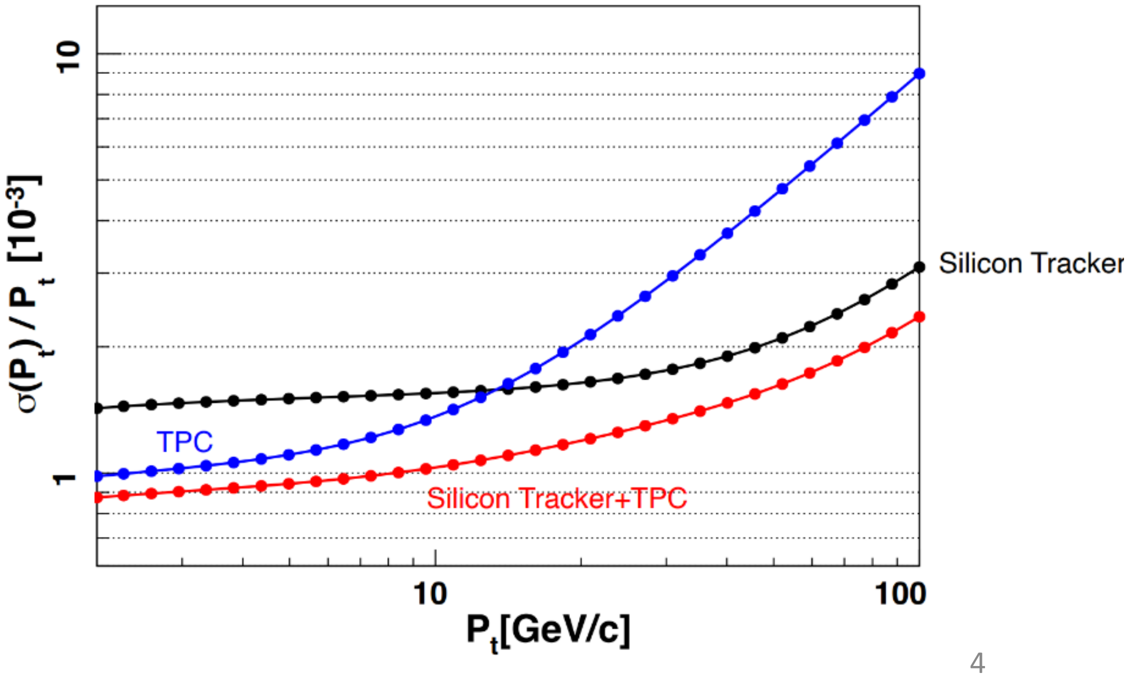
Chapter 5 Gaseous trackers

Physics requirement - 1

- 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%

	Processes @ c.m.s.	Domain	Total Det. Performance	Sub-D
H->ss/cc/sb	vvH @ 240 GeV	Higgs	PFA + JOI (Jet origin id)	All sub-D, especially VTX
H->inv	qqH	Higgs/NP	PFA	All
Vcb	WW@ 240/160 GeV	Flavor	JOI + Particle (lepton) id	All
W fusion Xsec	vvH @ 360 GeV	Higgs	PFA + JOI	All
α_S	Z->tautau @ 91.2 GeV	QCD	PFA: Tau & Tau final state id	ECAL + Tracker material
B->DK	91.2 GeV	Flavor	PFA + Particle (Kaon) id	All, especially Tracker & ToF
Weak mixing angle	Z	EW	JOI	All
Higgs recoil	llH	Higgs	Leptons id, track dP/P	Tracker, All
H->bb, cc, gg	vvH	Higgs	PFA + JOI	All
	qqH	Higgs	PFA + JOI + Color Singlet id	All
H->di muon	qqH	Higgs	PFA, Leptons id	Calo, All
H->di photon	qqH	Higgs	PFA, Photons id	ECAL, All
W mass & Width	WW@160 GeV	EW	Beam energy	NAN
Top mass & Width	ttbar@360 GeV	EW	Beam energy	NAN
Bs->vvPhi	Z	Flavor	Object in jets; MET	All
Bc->tauv	Z	Flavor	-	All
B0->2 pi0	Z	Flavor	Particle/pi-0 in jets	ECAL

Physics benchmark for reference TDR



Physics requirement - 2

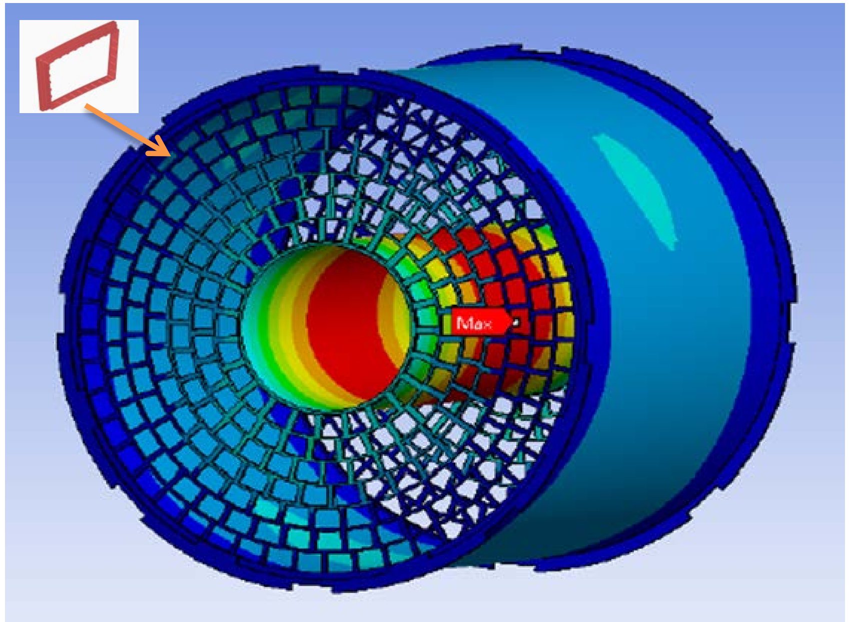
- CEPC operation stages: **10-years Higgs → 2-years Z pole → 1-year W**
- CEPC phy./det. TDR (preparation)
  - Physics and detector concept designed under the principle.
  - Requirements may be with regard to runs of Higgs and Z-pole separately.
    - Mandatory requirements MUST be met.
    - Detector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

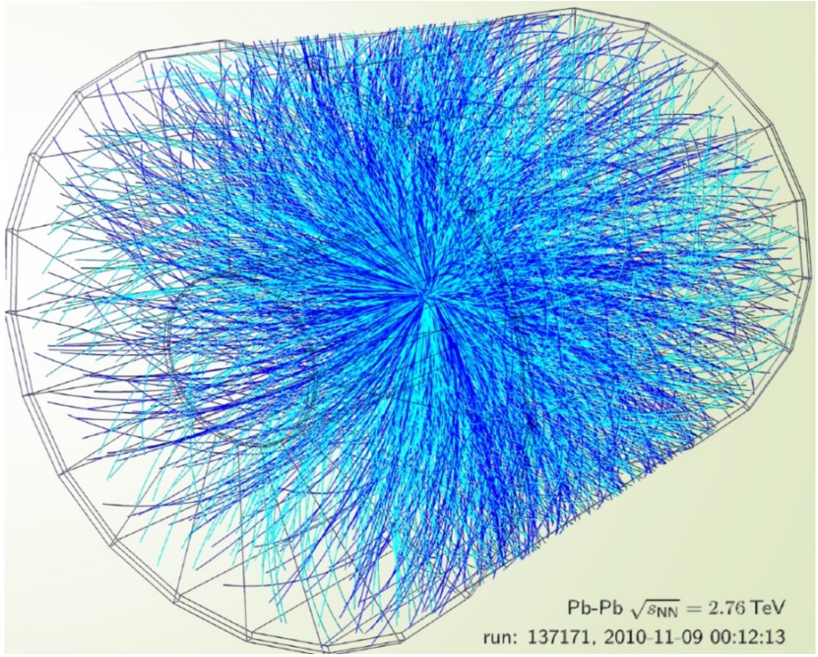
CEPC- TDR p116

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



Modular design



Time Projection Chamber

Drift Chamber

Technology survey and our choices

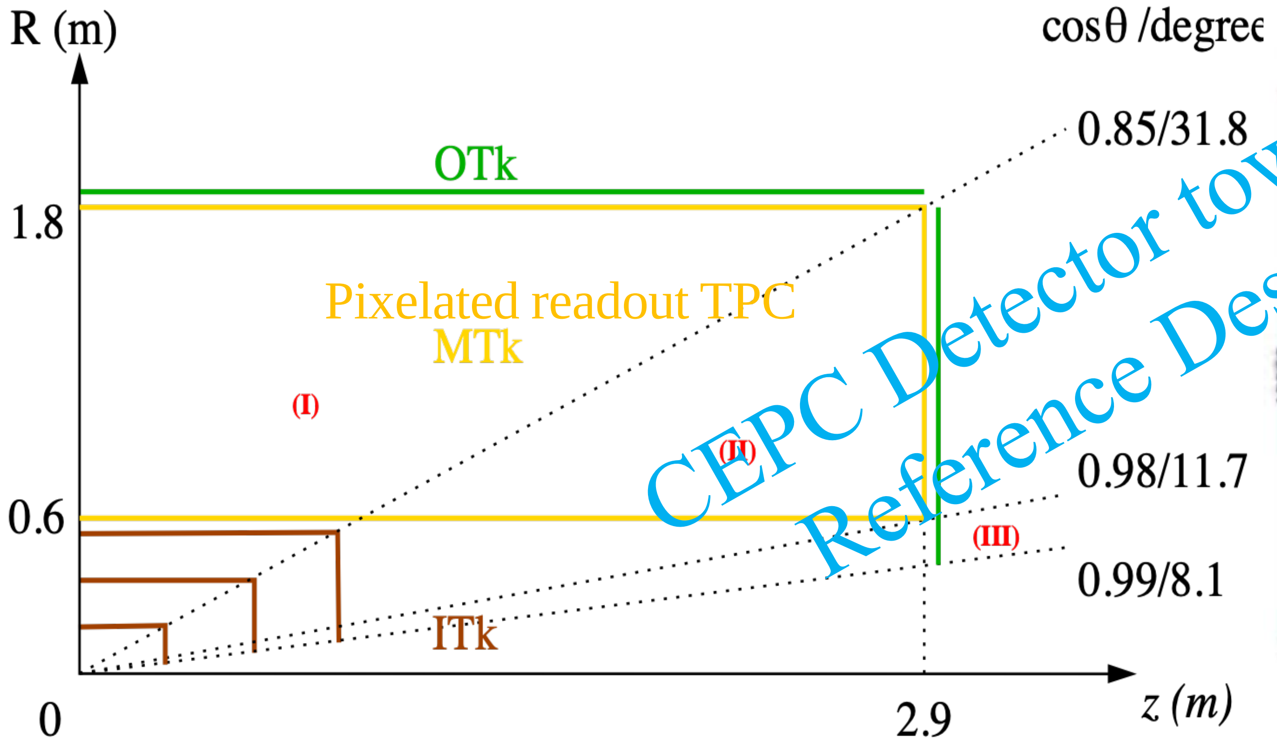
- Considering the technical challenges, performance, risk of detector
  - Pixelated readout TPC is as the **baseline track** detector in CEPC ref-TDR.
  - DC is as the **alternative** track detector at Tera-Z.

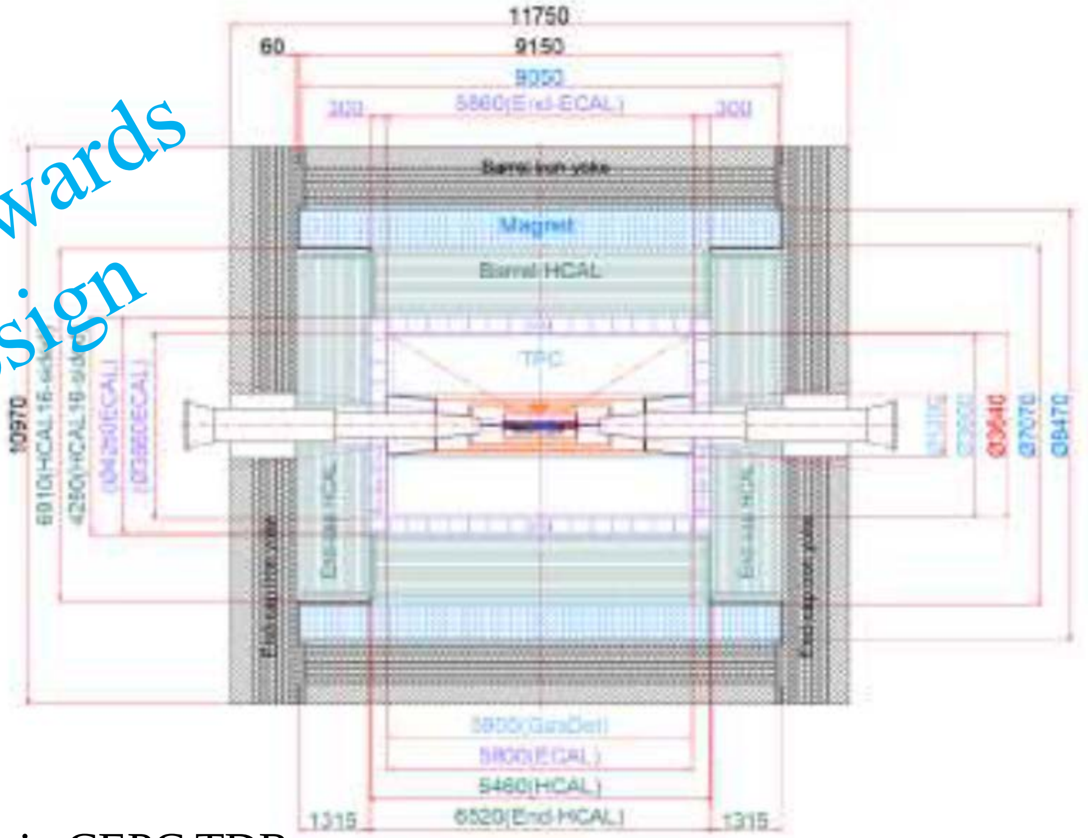
	TPC	DC
Material budget of barrel	●●●●●	●●●○○
Number of hits per track	●●●●●	●●●○○
Modular readout design	●●●●○	●●●○○
Momentum resolution at Higgs	●●●●○	●●●◐○
Hit separation in z	●●●●○	●●●○○
xy-resolution	●●●●○	●●●●○
Overall installation	●●●●○	●●●○○
Drift time	●●●○○	●●●●○
PID at Tera-Z in 2T	●●●●○	●●●●○
Distortion at Tera-Z in 2T	●●●○○	●●●◐○

Preliminary comparison

Baseline track detector: Pixelated TPC

- The track detector system's geometry finalized.
  - All of physics simulation used the updated geometries for CEPC TDR document
  - Silicon combined with gaseous chamber as the tracker and PID
  - **Baseline:** Pixelated readout TPC as the **main track (MTK)** from radius of 0.6m to 1.8m





CEPC Detector towards Reference Design

Geometry of the track detector system in CEPC TDR

Technical challenges and R&D efforts

Main Technical Challenges

- **Performance studies of the pixelated readout TPC (Baseline)**

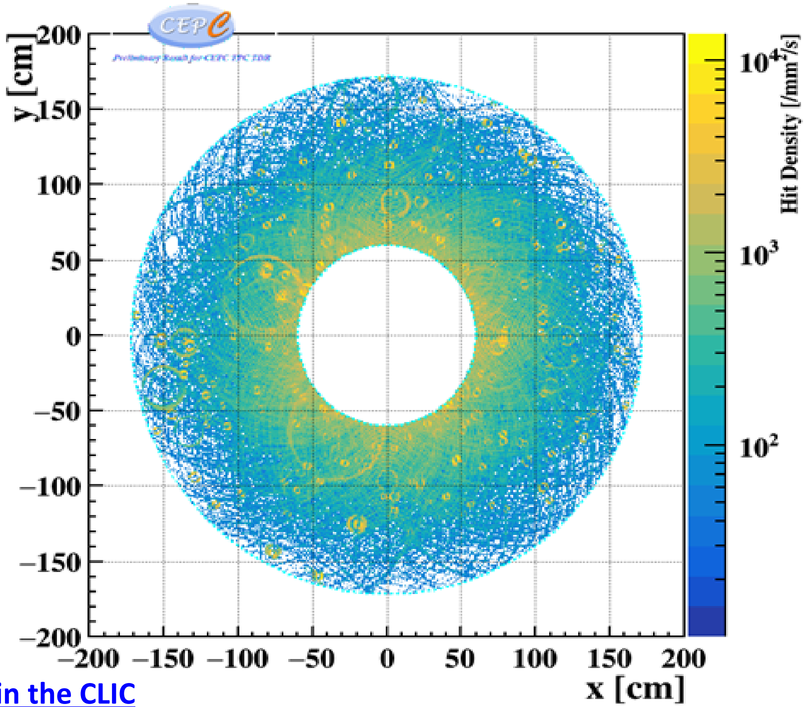
Critical key issues:

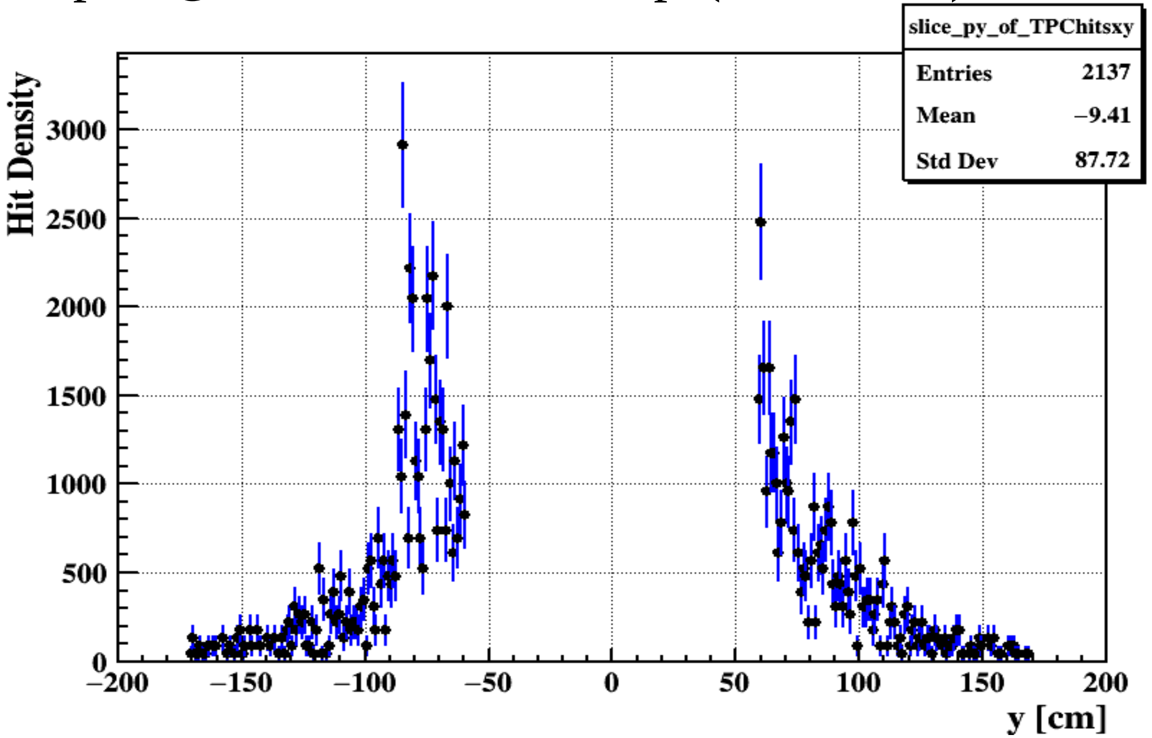
  - **Material budget at endcape/barrel √**
  - **Occupancy and hit density at Tera-Z √**
  - **Ion backflow suppression √**
  - **Running at 2 Tesla √**
  - **Improved PID √**
  - **Reasonable channels and power consumption (ongoing)**

- **Performance studies of DC (Alternative at Tera-Z)**
  - **dN/dx for PID √**
  - **High prevision time resolution (ns) FEE √**
  - **Risk the 5.8m wires and tension (ongoing)**

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).

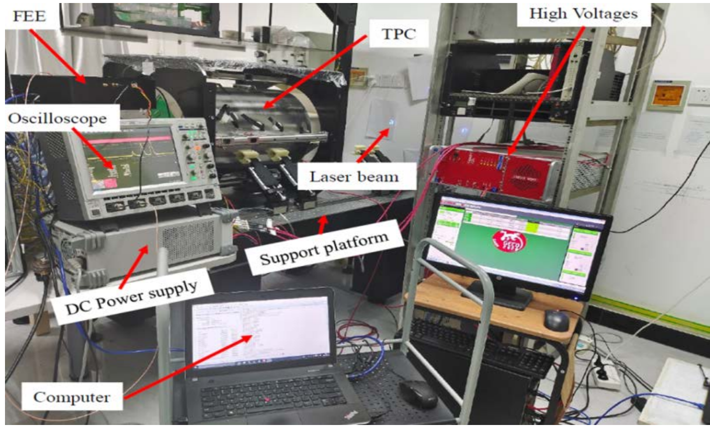


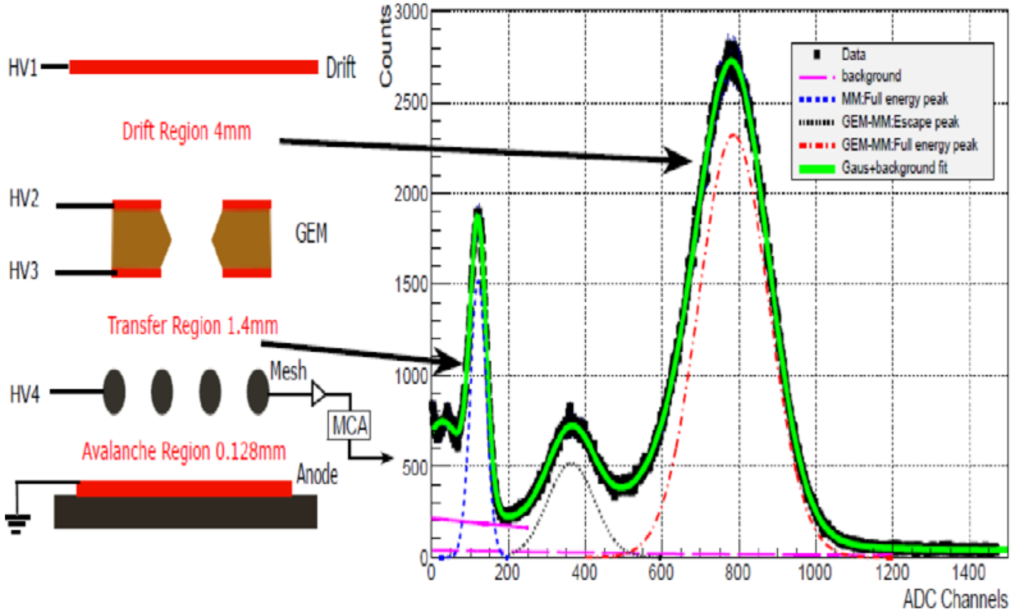


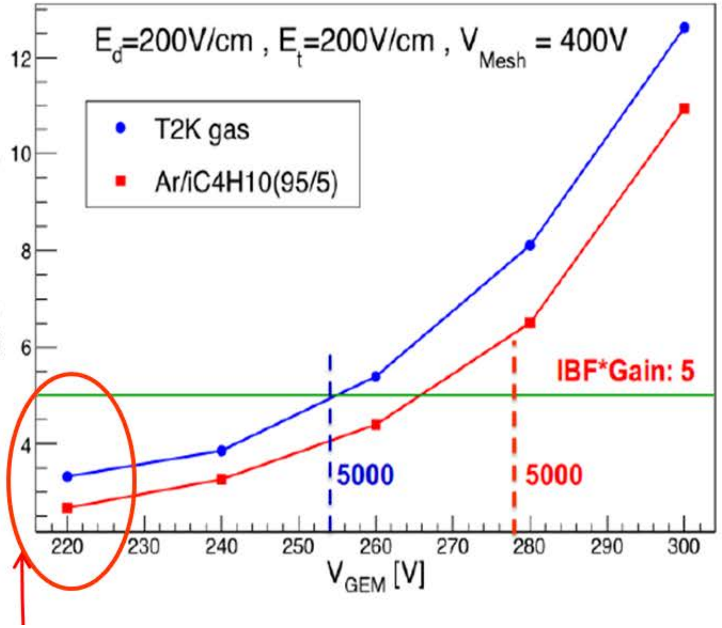
Cite#1 Occupancy in the CLIC
Cite#2 https://doi.org/10.1088/1748-0221/12/07/P07005
Cite#3 GridPix detectors

Ion back flow R&D and results

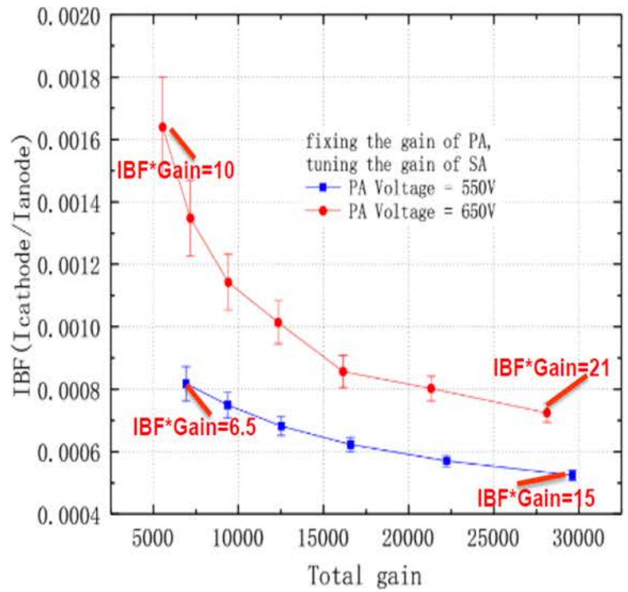
- Achievement by far from TPC module and prototype:
  - Supression ions hybrid TPC module
    - **IBF × Gain ~1 at Gain=2000 validation** with TPC module
  - Spatial resolution of **$\sigma_{r\varphi} \leq 100$ µm** by TPC prototype
  - dE/dx for PID: <3.6% (as expected for CEPC baseline detector concept)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







IBF of double mesh MM @USTC/Jianbei Liu



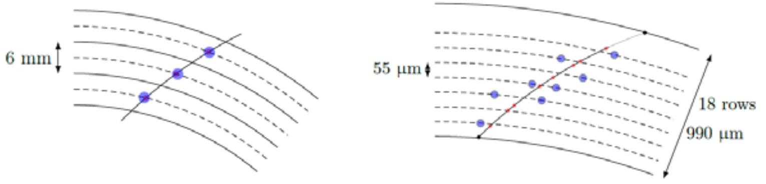
Cite#4: DOI:10.1016/j.nima.2020.164282
Cite#5: CERN-OPEN-2021-012. 2021
Cite#6: IJMPA 36.22 (20212142015

Hybrid TPC module and Double-mesh detector module

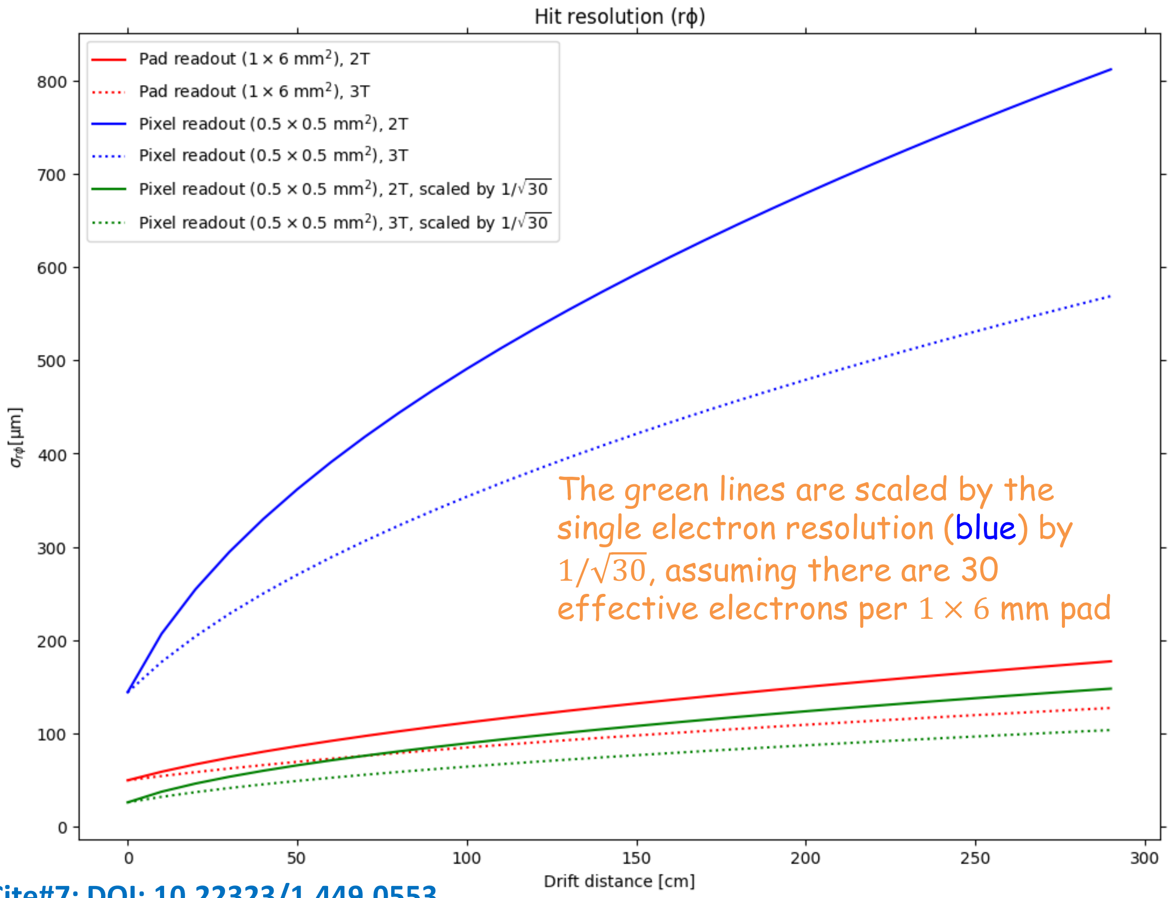
Tera-Z at 2T R&D and results

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:

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

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

Pixel readout:

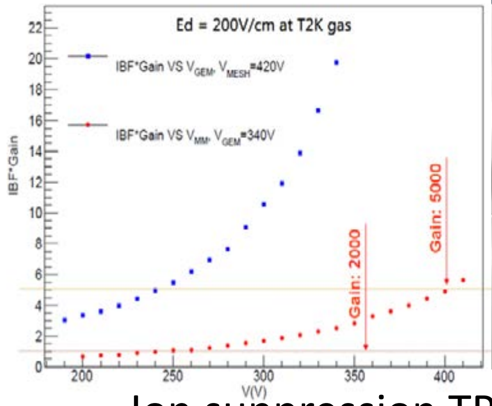
$$\sigma_r^{\text{pixel}} = \sigma_{r\phi}^{\text{pixel}} = \sqrt{(\sigma_{r\phi 0}^{\text{pixel}})^2 + LD_{r\phi}^2\left(\frac{4.0\ \text{T}}{B}\right)^2}$$

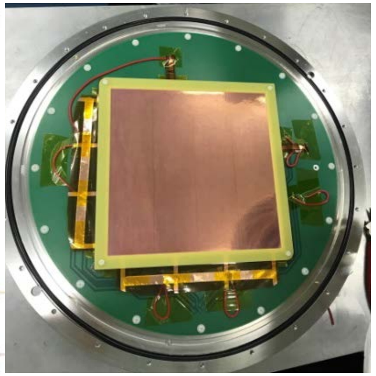
- $\sigma_{r\phi 0} = \frac{500}{\sqrt{12}} = 144\mu m$
- $D_{r\phi} = 46.9\mu m/\sqrt{cm}(2T), 32.3\mu m/\sqrt{cm}(3T)$

Cite#7: DOI: 10.22323/1.449.0553

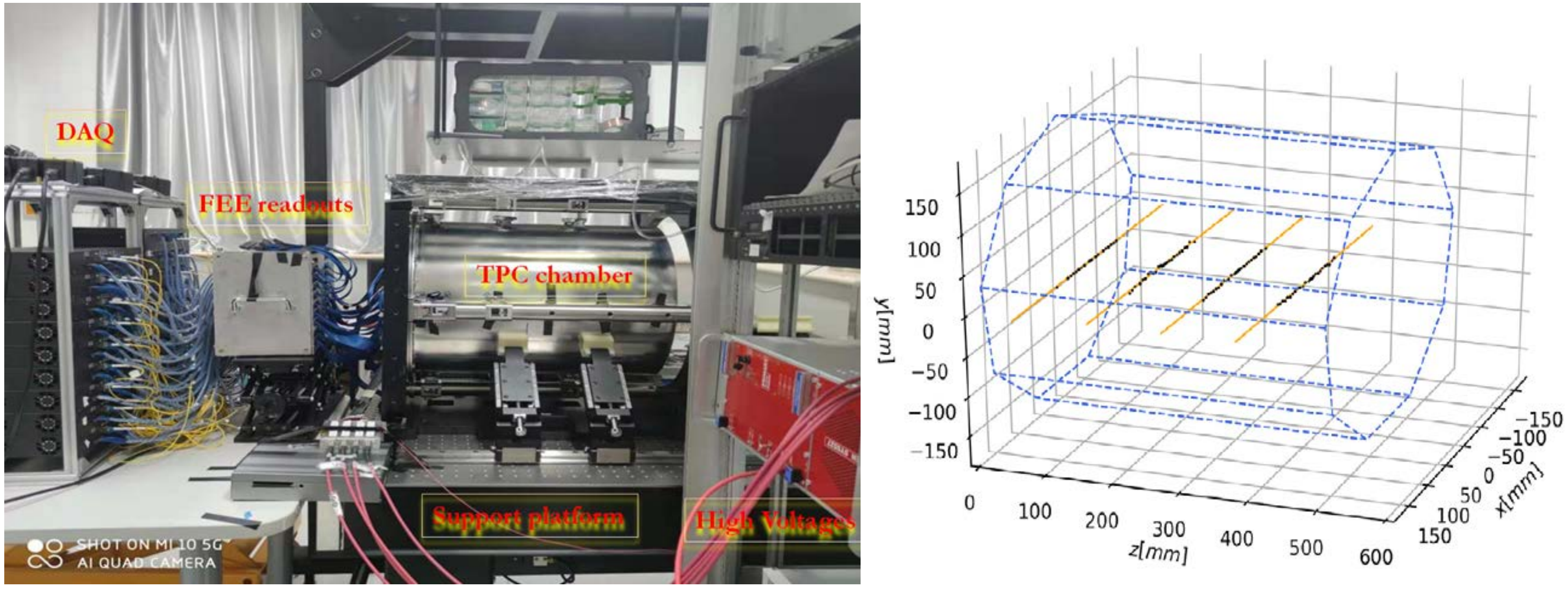
TPC prototype R&D efforts and results

- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to **TPC prototype R&D for Higgs and Tera-Z**
  - 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

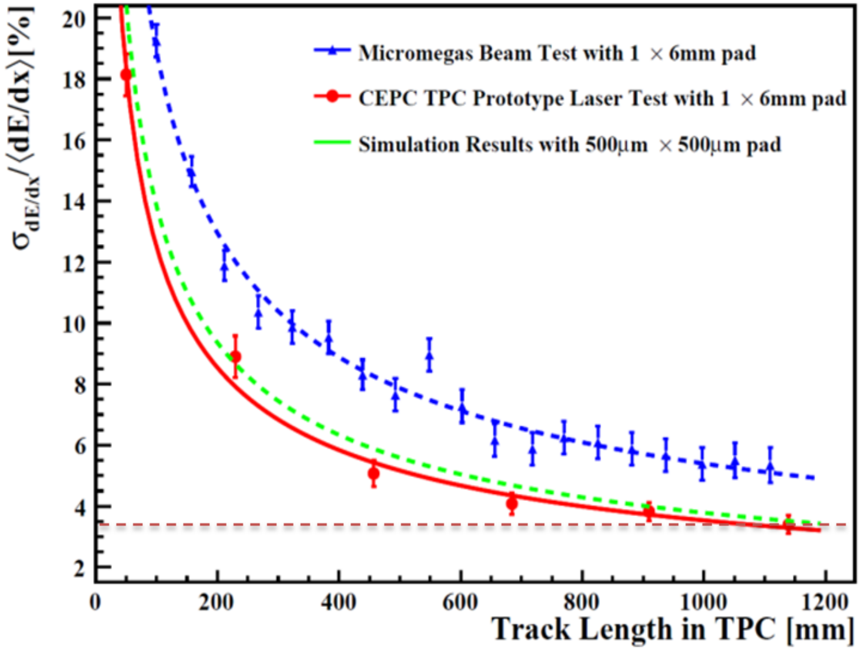




Ion suppression TPC module R&D



TPC prototype with integrated 266nm UV laser

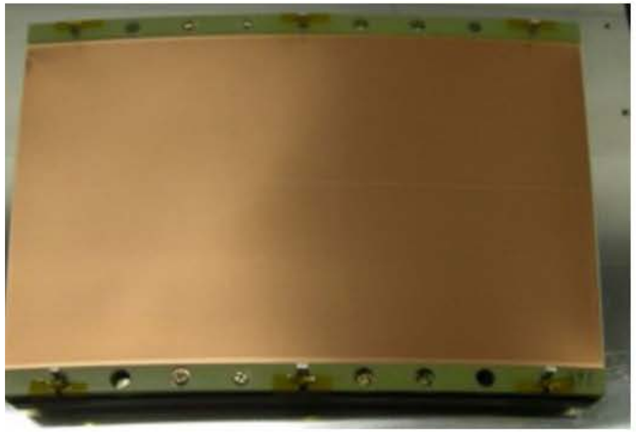
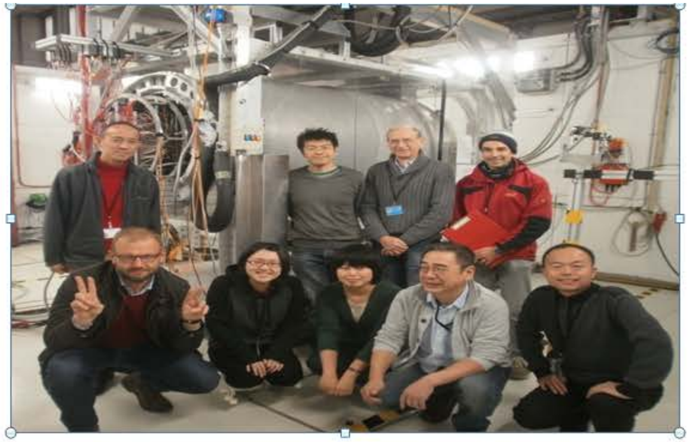
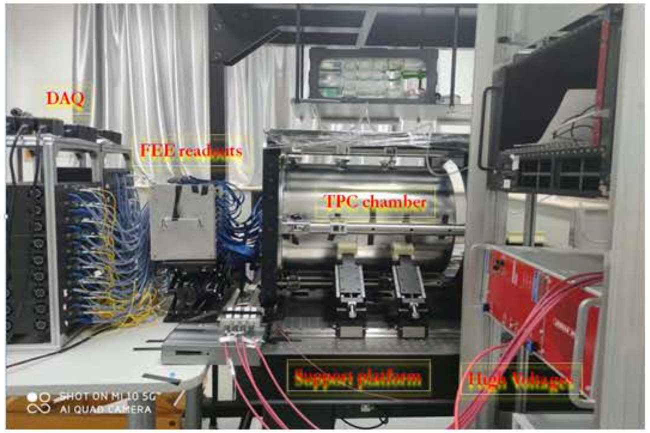


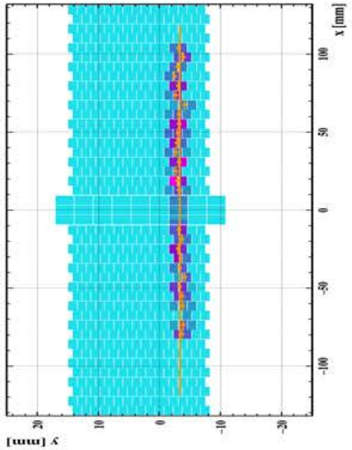
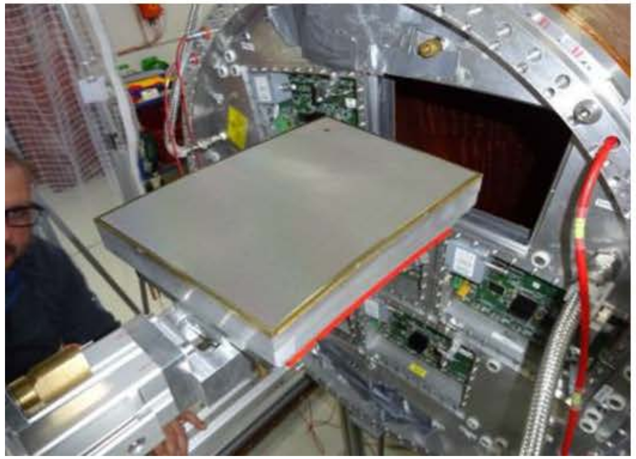
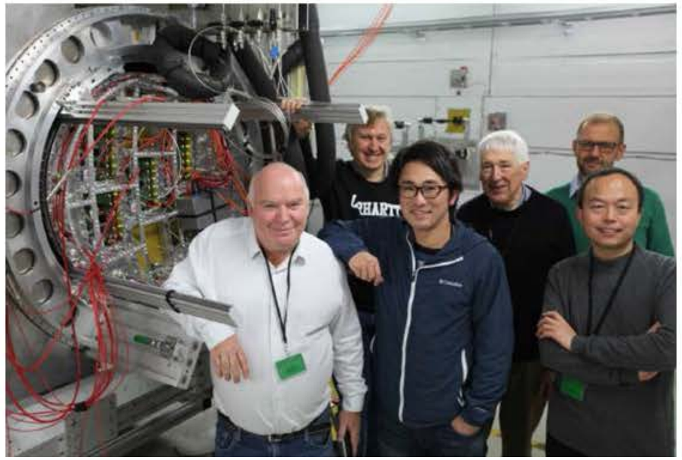
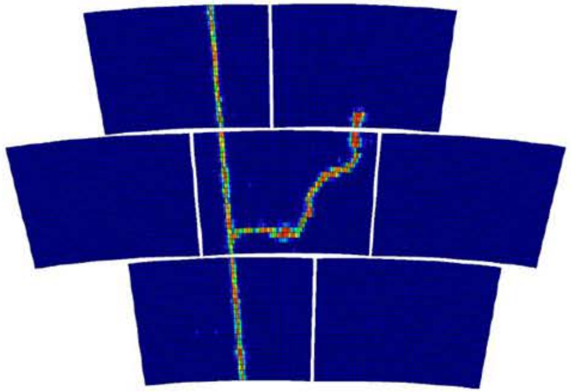
dE/dx results

Activity international collaboration

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

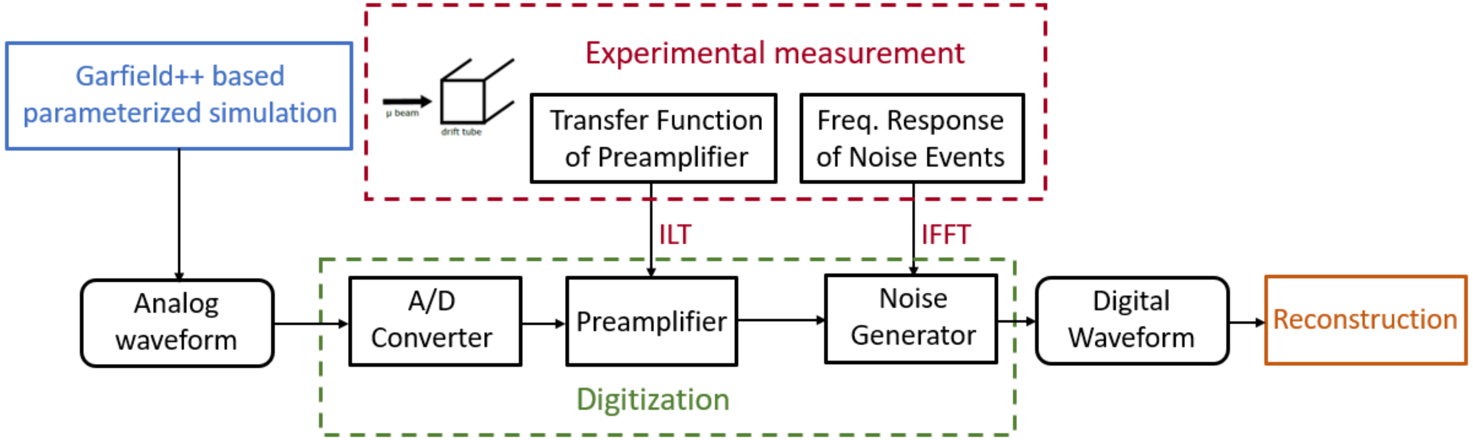
- Activity collaboration: Pixelated readout and Pad readout from IHEP and LCTPC collaboration
  - Large Prototype setup have been built to compare different detector readouts for Tera-Z
  - PCMAG: B < 1.0T, bore Ø: 85cm, Spatial resolution of $\sigma_{r\phi} \leq 100$ μm
  - Collaboration implement improvements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

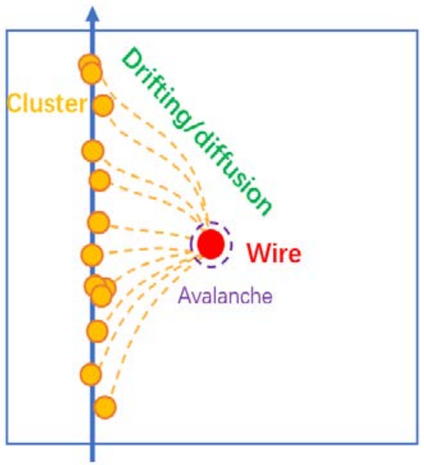






DC R&D efforts and results

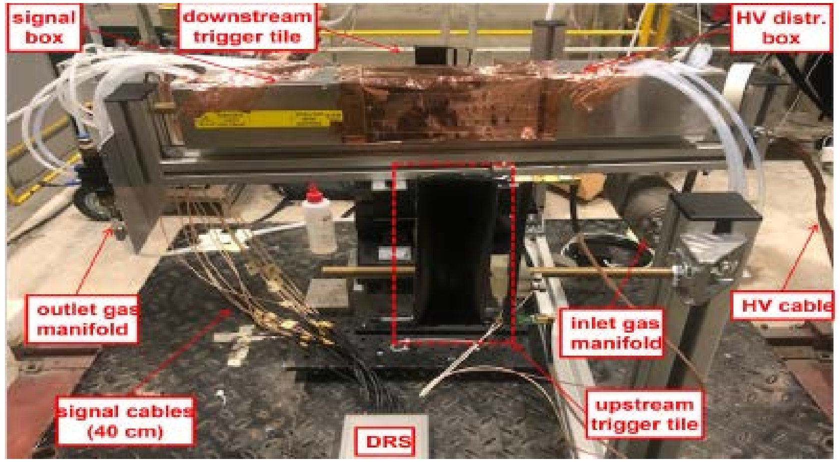
- Develop sophisticated software tools for DC PID simulation

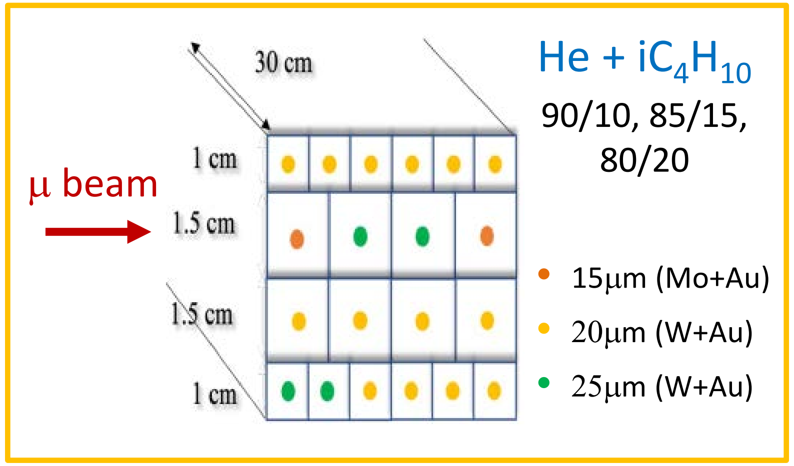


DC cell

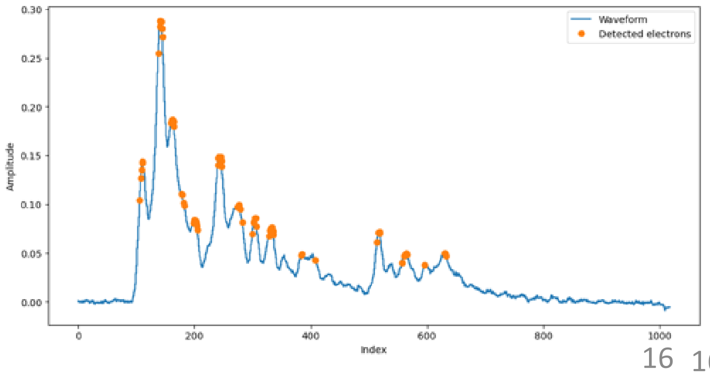


- International collaboration of the beam test





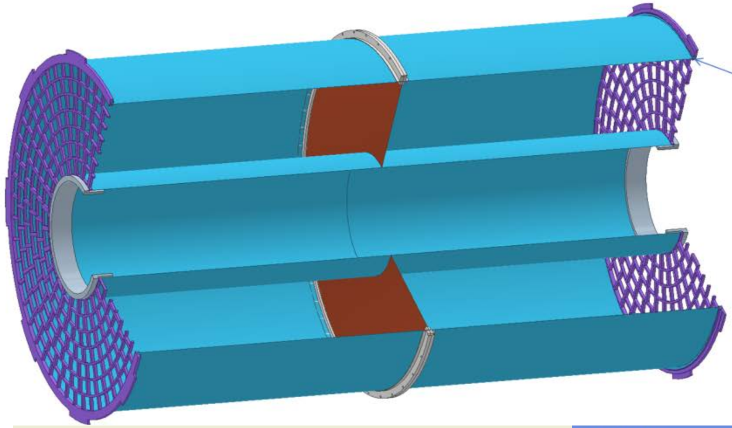
Waveform reconstruction with ML (domain adaptation)

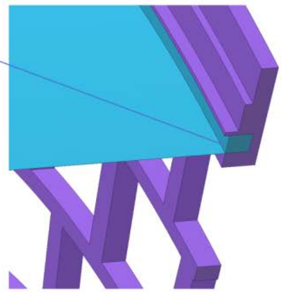


Detailed design and performance of Baseline: TPC

Detailed design of mechanics and cooling

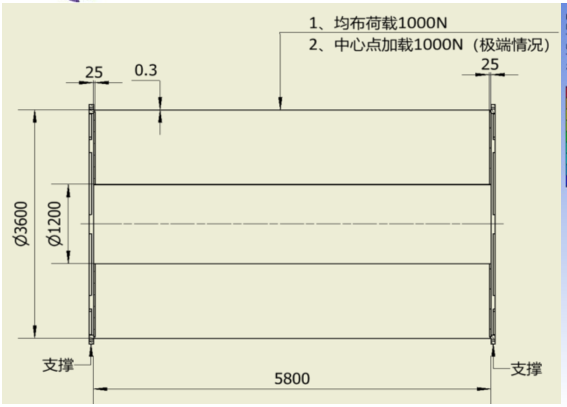
- Consideration of new Carbon Fiber barrel instead of the honeycomb barrel (**~2% X_0**)
- **Ultra-light material** of the TPC barrel : **0.59% X_0 in total, including**
  - FEA preliminary calculation: 0.2mm carbon fibber barrel can tolerant of LGAD OTK (**100Kg**)
- Optimization of the connection back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

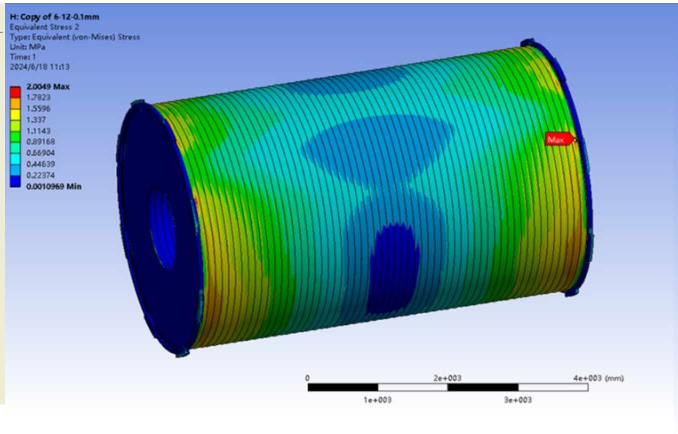


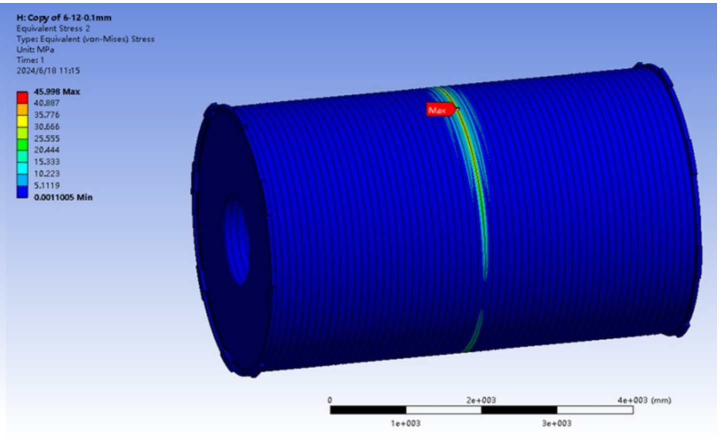


Material budget of TPC barrel

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**



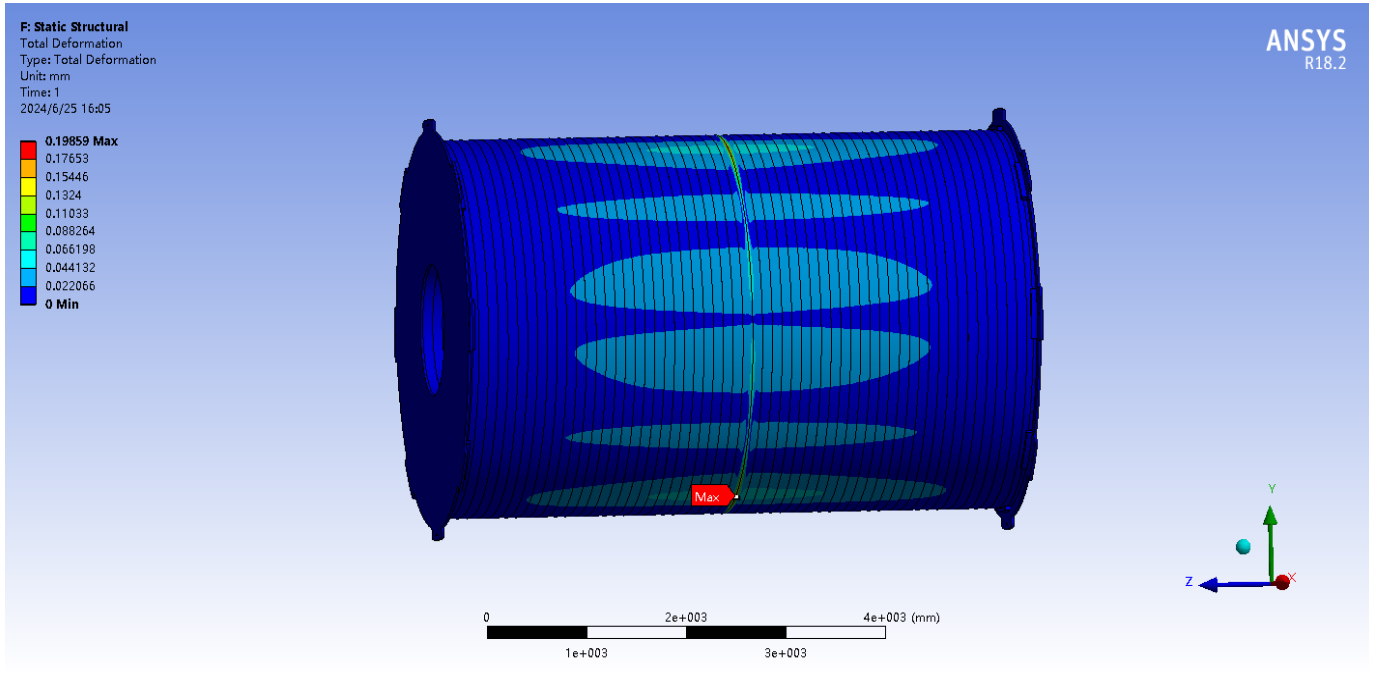


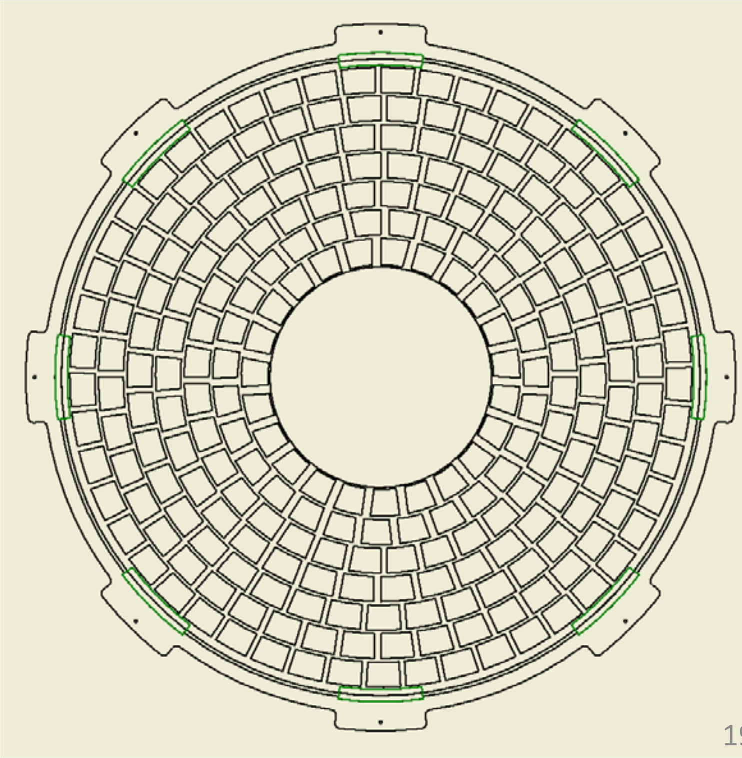


FEA analysis results of TPC

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.



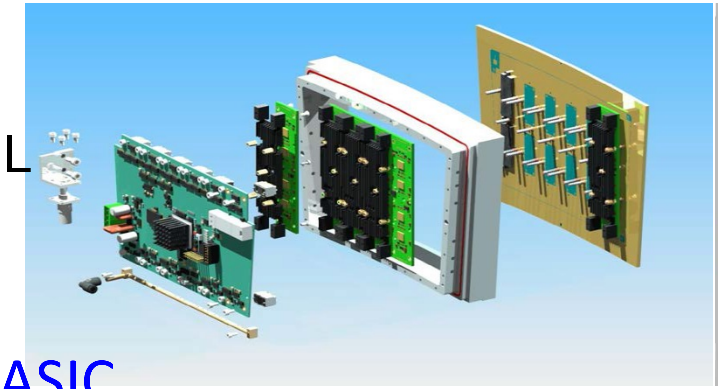


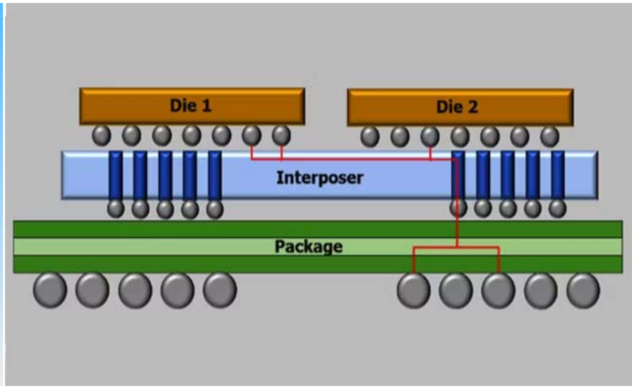
Detailed design of the readout

Parameters	Higgs run	Z pole run
B-field	3.0T	2.0T
Readout size (mm)/All channels	0.5mm×0.5mm /2×3×10^7	0.5mm×0.5mm /2×3×10^7
Material budget barrel (X_0)	0.59%	0.59%
Material budget endcap (X_0)	15%	15%
Points per track in rφ	2300	2300
σ in rφ	120μm (full drift)	400μm (full drift) w. distortion
σ in z	≃ 0.1 – 0.4 mm (for zero – full drift)	≃ 0.2 – 0.8 mm (for zero – full drift)
2-hit separation in rφ	0.5mm	0.5mm
K/π separation power @20GeV	3 σ	3 σ
dE/dx	< 3.0%	< 3.0%
Momentum resolution normalised: $\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$	a = 1.9 e -5	a = 4.2 e -5
	b = 0.8 e -3	b = 1.2 e -3

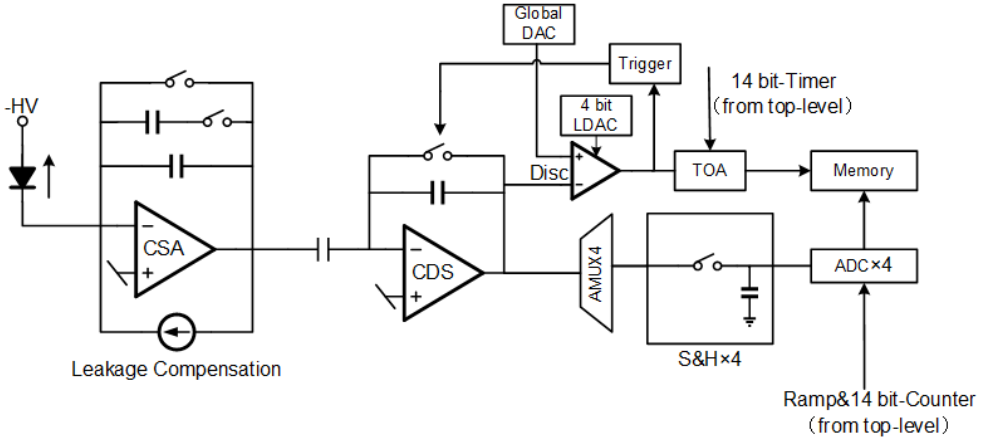
Detailed design of electronics and BEC

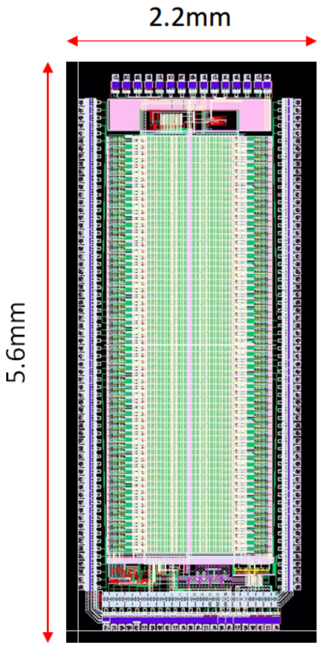
- Pixel Readout Electronics
  - Multi-ROIC chips + Interposer PCB as RDL
  - High metal coverage
  - Four-side buttable

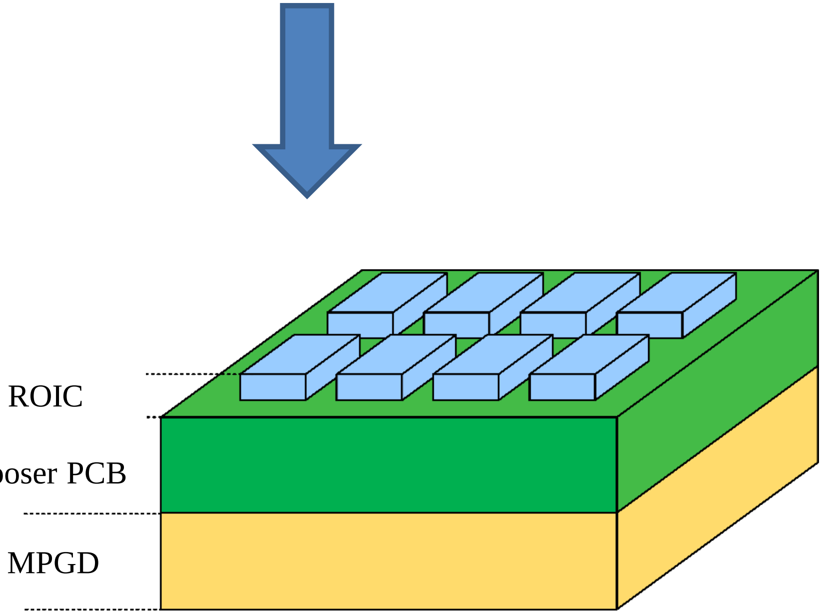




- Low power Energy/Timing measurement ASIC
  - Low noise: ~100 e noise
  - 5 ns drift time resolution
  - Low power: 100 mW/cm2 (250uW/ch)





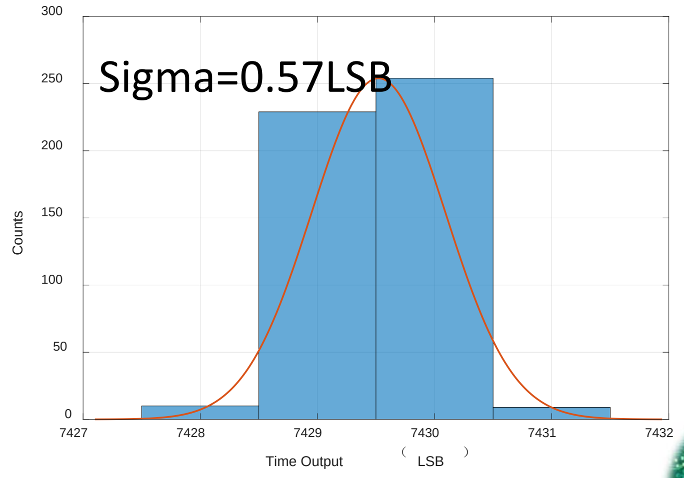


Detailed design of electronics and BEC

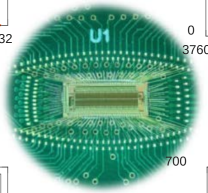
FEE ASIC: TEPIX—Test Results in May

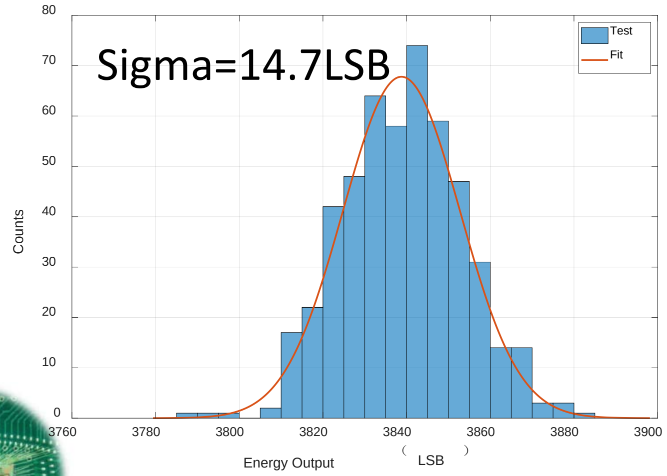
- Power Consumption ~ 0.5mW/ch
- Timing ~ <1LSB(10ns)
- Noise ~ < 300e (even high gain)

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

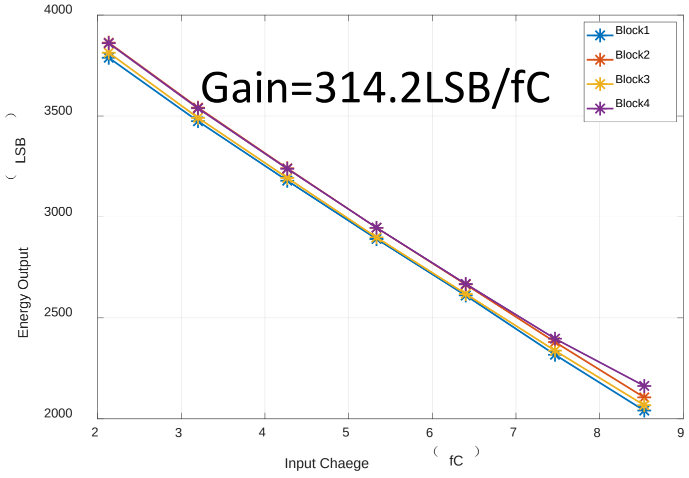


Timing Results

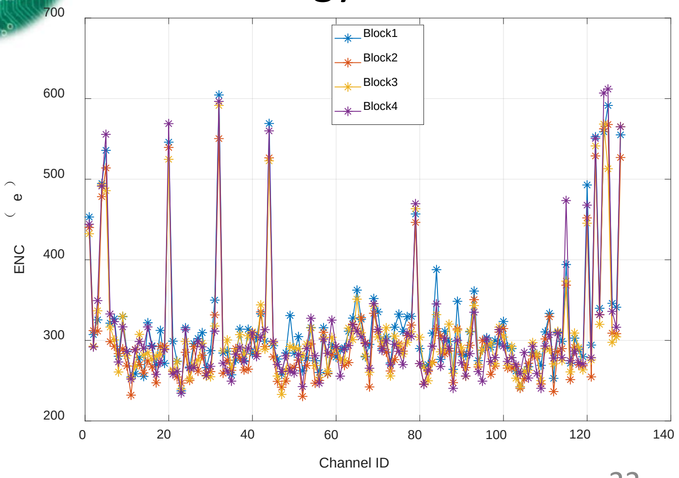




Energy Results



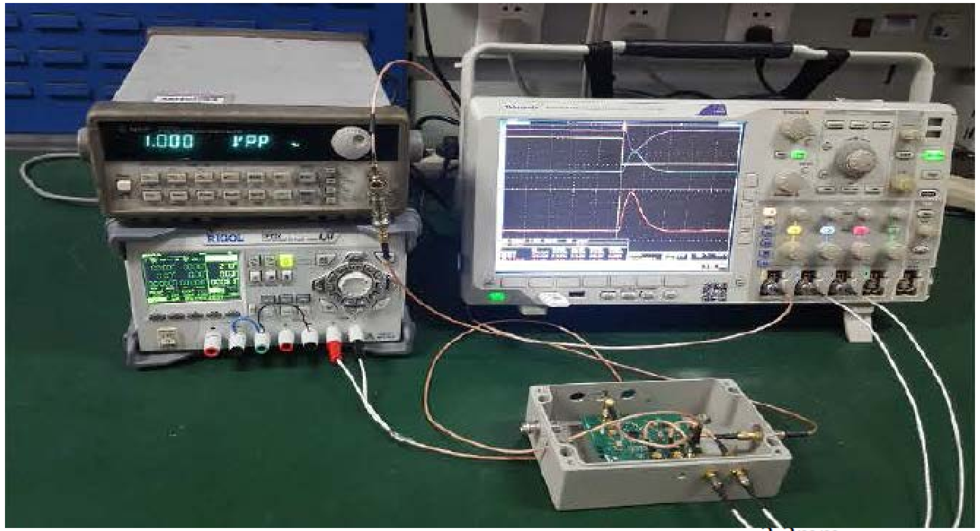
Gain

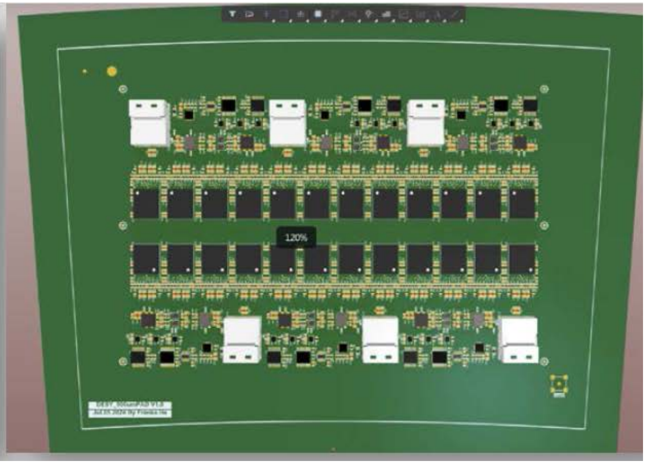


Noise

Validation 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
    - 500μm×500μm pixel readout designed
    - Time resolution: 14bit (5ns bin)
    - Power consumption: **~100mW/cm^2**
- **Prototyping pixelated readout TPC detector**
  - The validation of the prototype assembled for beam test





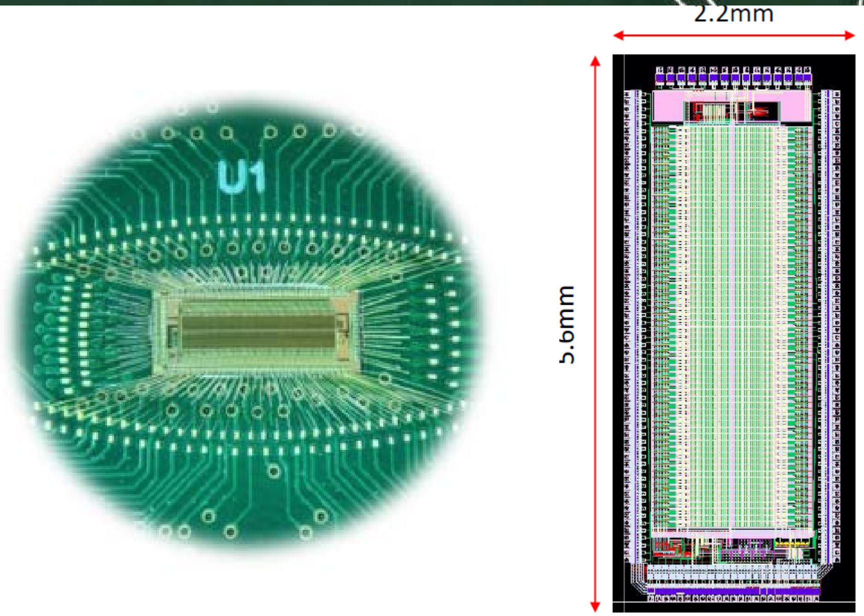
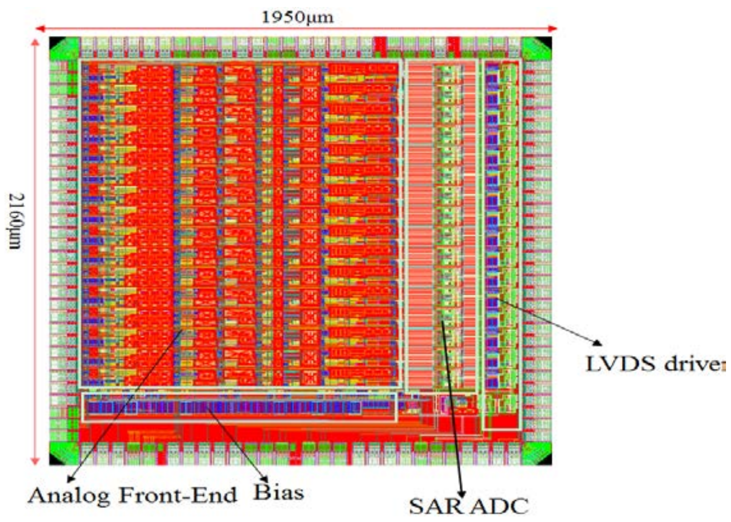


Photo and layout of ASIC Chip R&D for TPC

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**

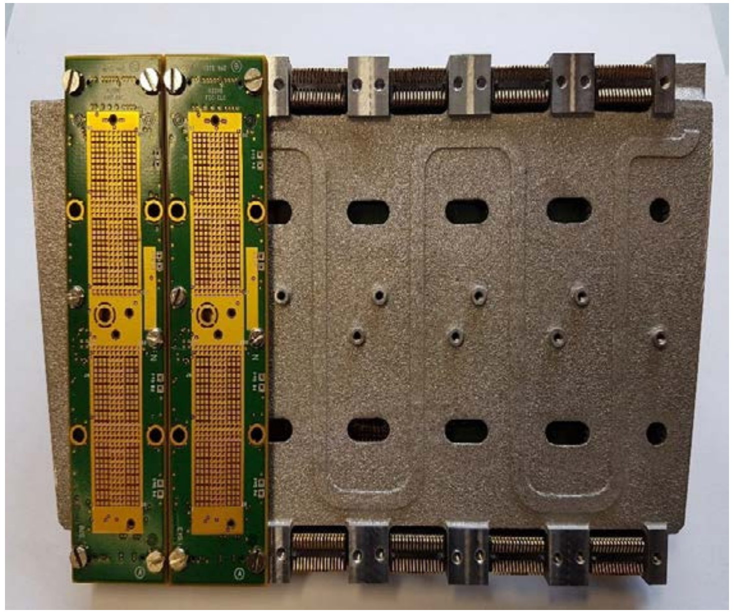
	PASA+ALTRO	Super-ALTRO	SAMPA	WASA_v1
TPC	ALICE	ILC	ALICE upgrade	CEPC
Pad Size	4x7.5 mm^2	1x6 mm^2	4x7.5 mm^2	1x6 mm^2
No. of Channels	5.7× 10^5	1-2 × 10^6	5.7 × 10^5	2 x×10^6
Readout Detector	MWPC	GEM/MicroMegas	GEM	GEM/MicroMegas
Gain	12 mV/fC	12-27 mV/fC	20/30 mV/fC	10-40 mV/fC
Shaper	CR-(RC)^4	CR-(RC)^4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

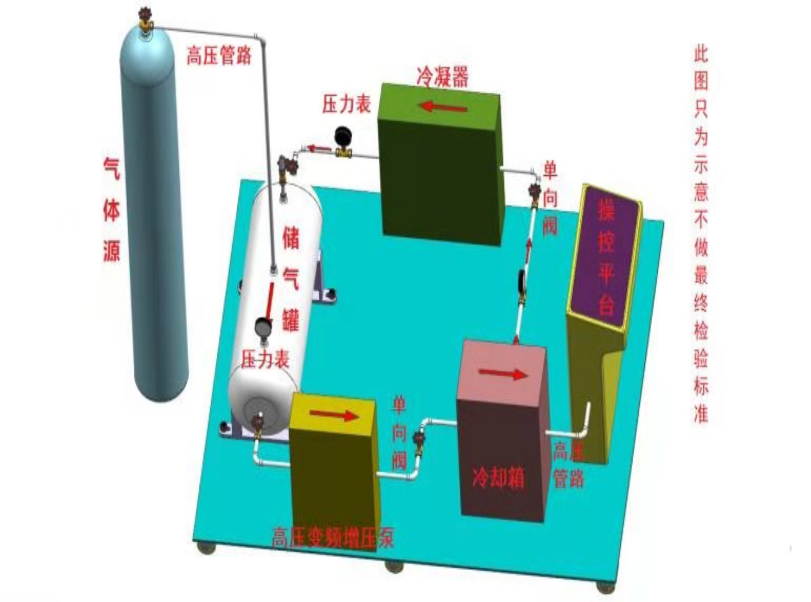


DOI: 10.1088/1748-0221/15/02/T02001
DOI: 10.1088/1748-0221/15/05/P05005

Detailed design of mechanic and cooling

- Readout electronics will require a cooling system. **2-phase CO_2-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**.



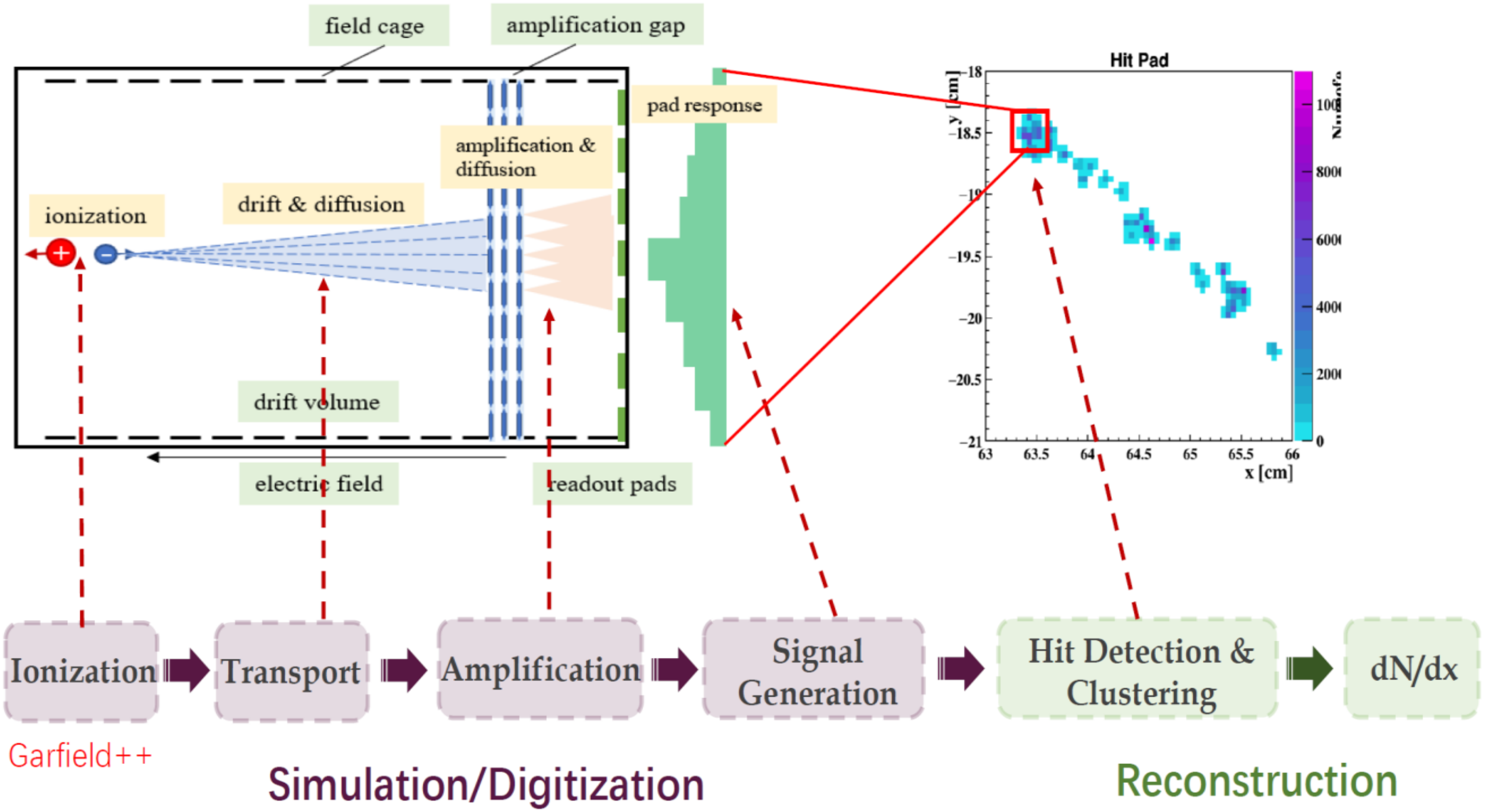


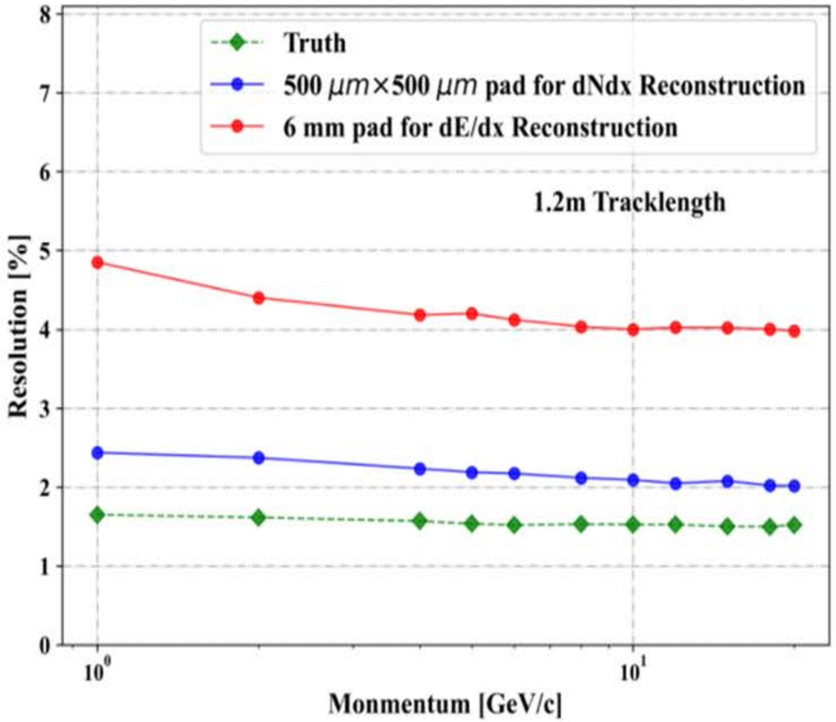
Cite#8: DOI 10.48550/arXiv.1403.7717
Cite#9: DOI 10.1088/1748-0221/10/08/P08001
Cite#10: DOI 10.1088/1742-6596/2374/1/012149

Performance from simulation

- 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**

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



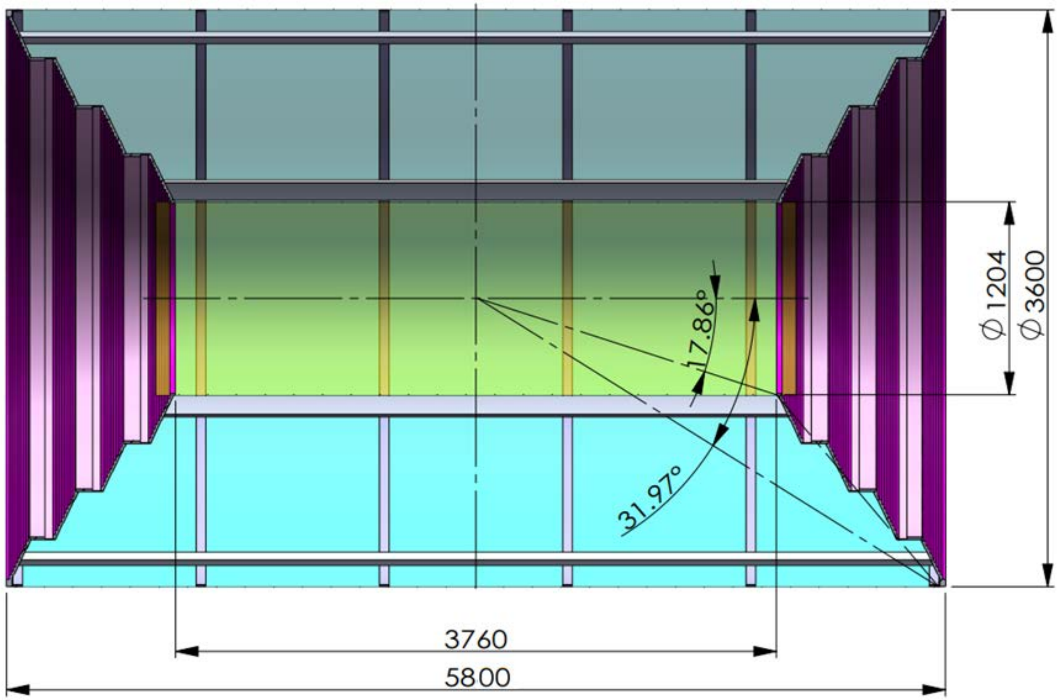


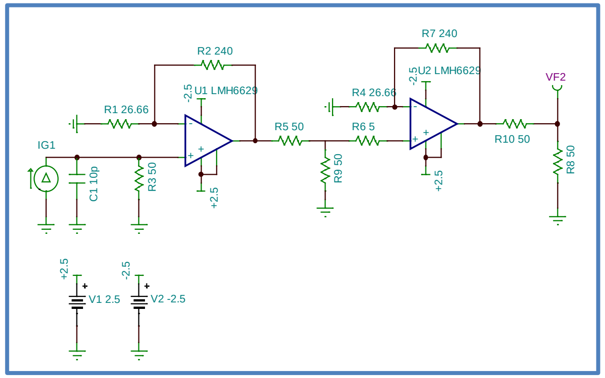
Simulation of TPC detector under 3T/2T and T2K mixture gas

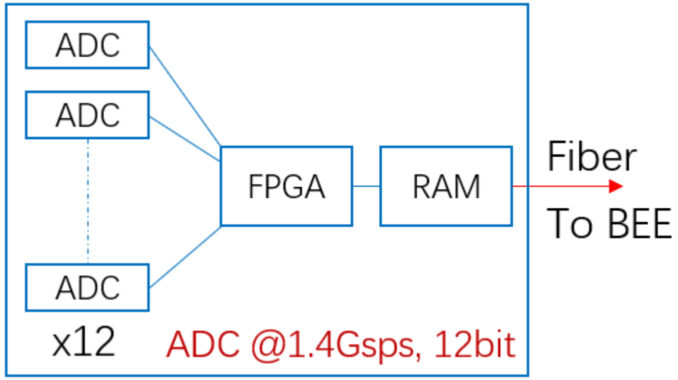
Cite#11: DOI: 10.22323/1.449.0553
Cite#12: EPS-HEP 2023 talk by Yue Chang

Detailed design and performance of Alternative at Tera-Z: DC

Detailed design of DC at Tera-Z







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

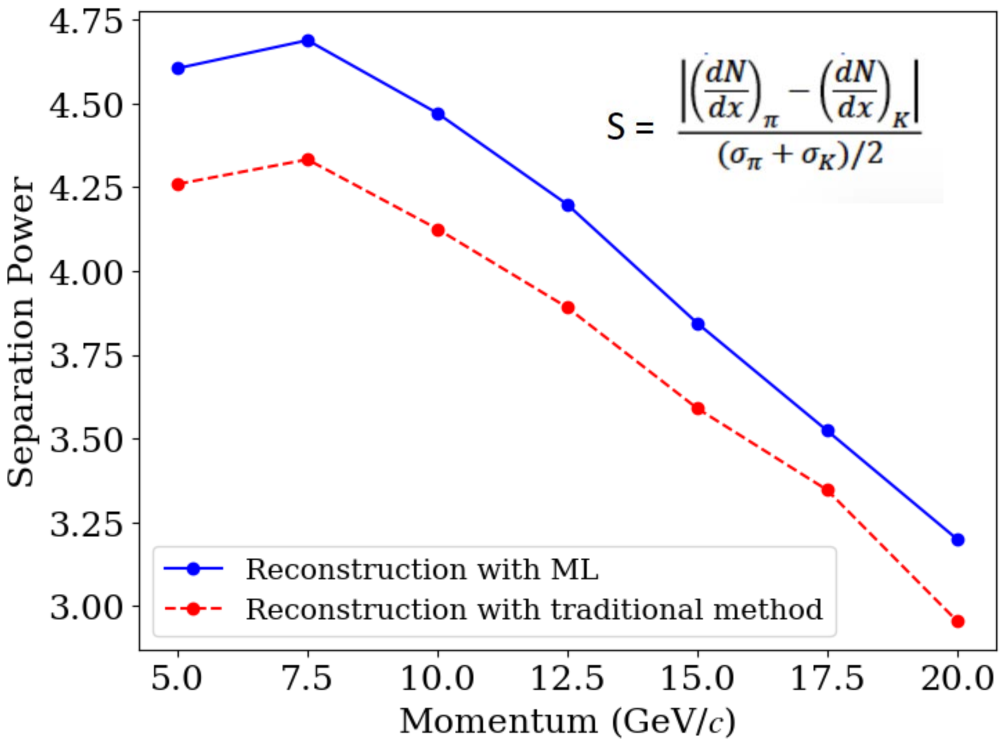
FEE-2:
ADC and FPGA board for data readout and buffering,
located in low dose region
0.5Gbps/12 channels

- 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

PID performance of DC

- 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

Research Team

- Core of the research team
  - 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
  - TPC: CIAE, Shandong University, Nankai University, Zhengzhou University and Liaoning University
  - DC: Wuhan University, Jilin University
  - 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
  - Optimization of the detector for CEPC TDR
  - Prototyping R&D and validation using FEE
    - mechanics, manufacturing, beam testing
  - Performance of the simulation and optimize deep learning algorithm
- Long term working plan
  - 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 traker 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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