Pixelated readout TPC technology R&D in CEPC Phy.&Det. TDR

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On behalf of the CEPC gaseous tracker R&D group

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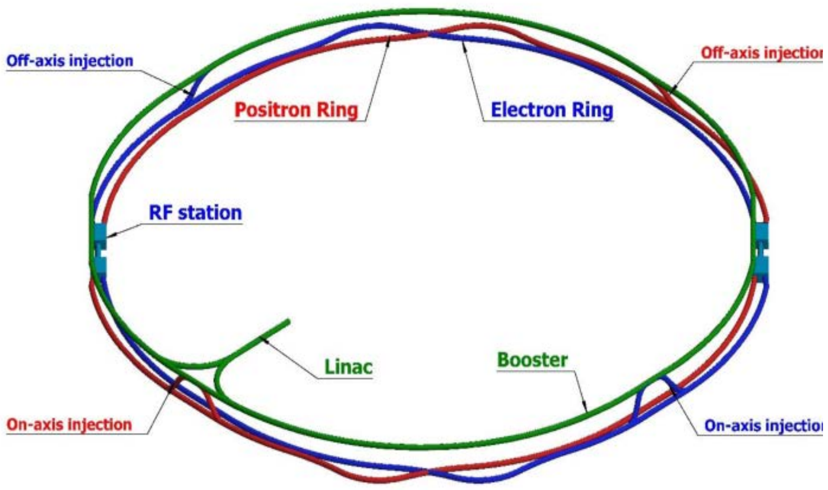
Content

- Motivation and physics requirements
- Status of TPC in CEPC TDR
- Simulation and prototype preparation
- Work plan and summary

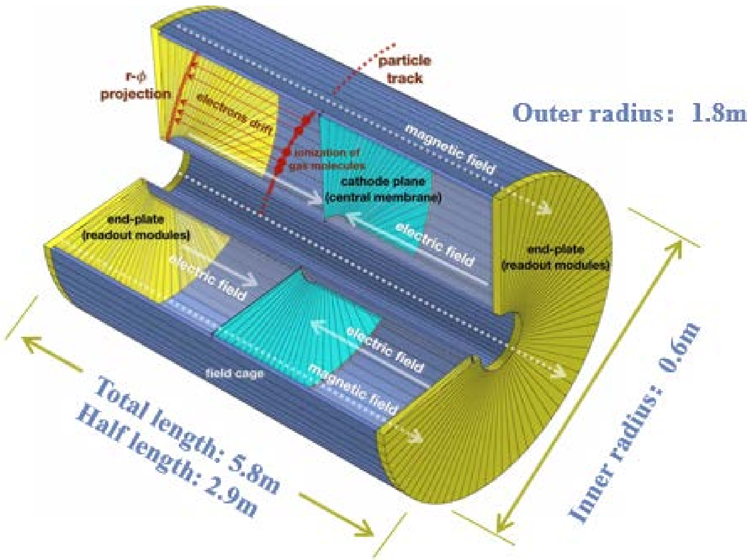
- **Motivation and physics requirements**

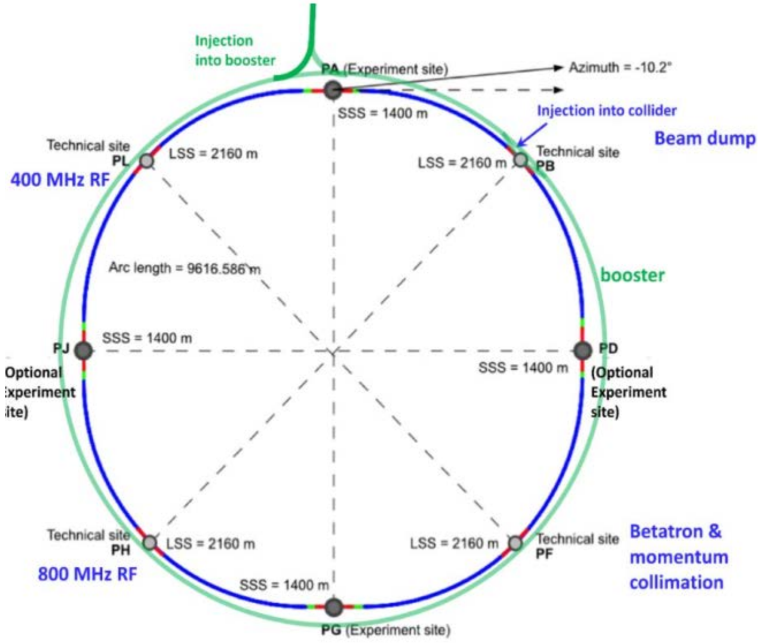
Motivation and physics requirements

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



Circular Electron Positron Collider (CEPC)





Future Circular Collider (FCCee)

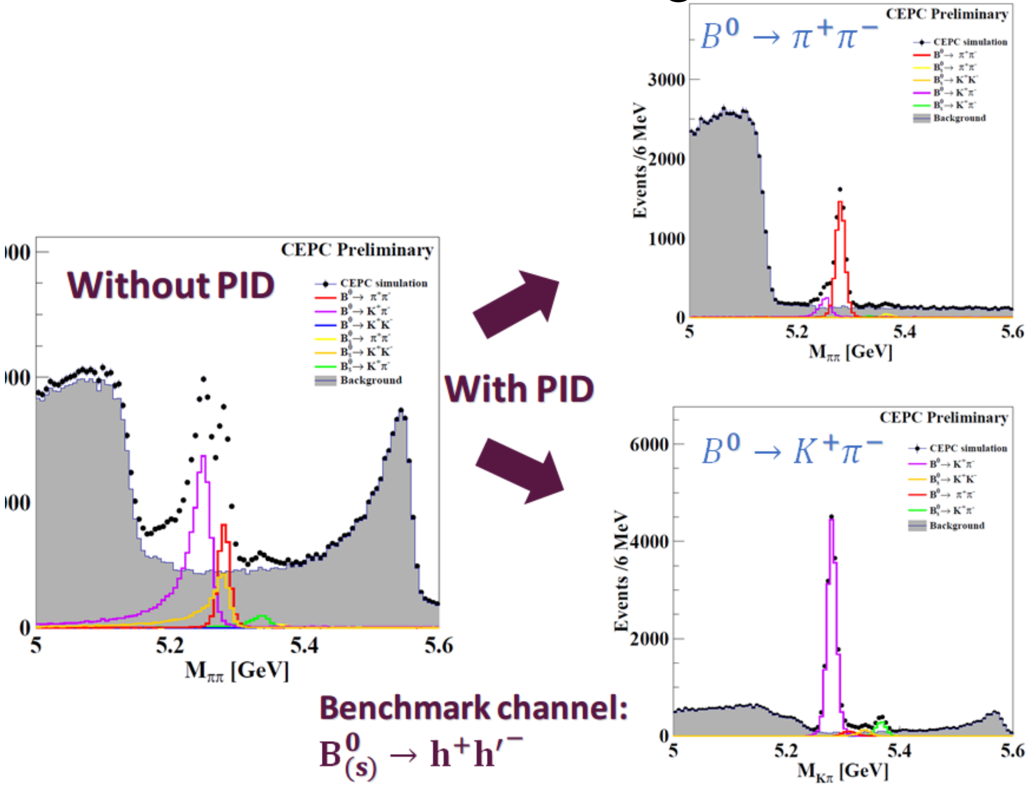
https://arxiv.org/abs/1811.10545

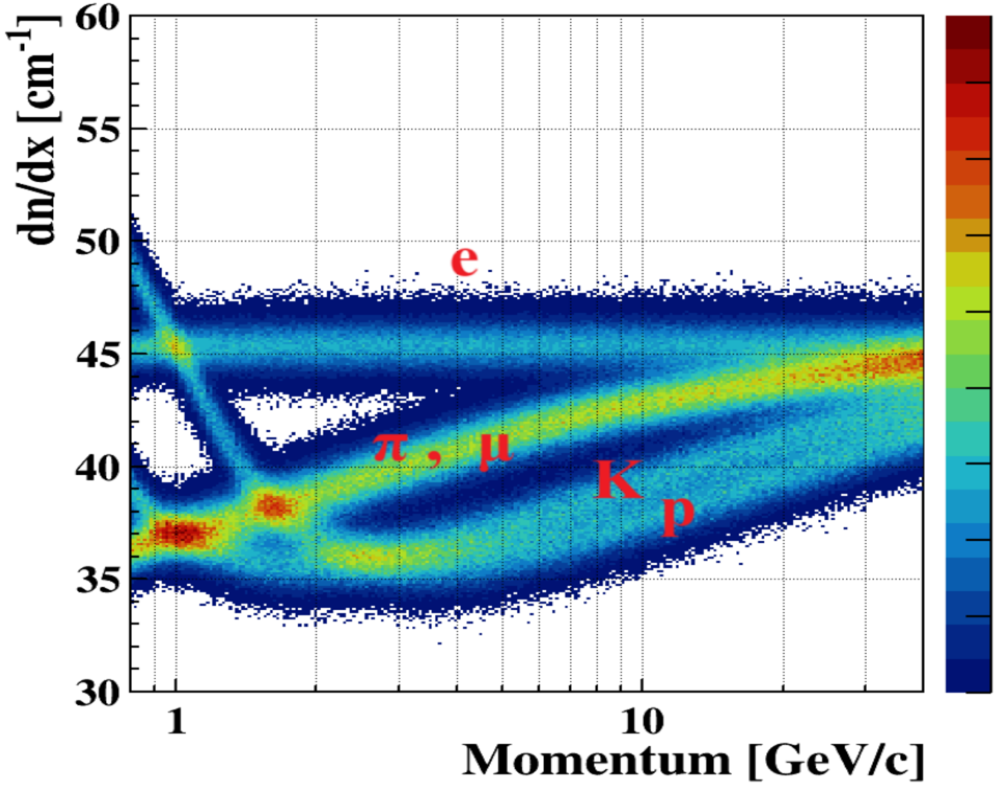
https://arxiv.org/abs/2203.08310

Motivation and physics requirements

- Circular e+e- collider operation stages in TDR: **10-years Higgs @3T → 2-years Z pole → 1-year W**
- Gaseous tracker leading contribution to PID and the high resolution: jet & differential
  - Pixelated readout and better than 2σ separation power between π and k for P using dn/dx

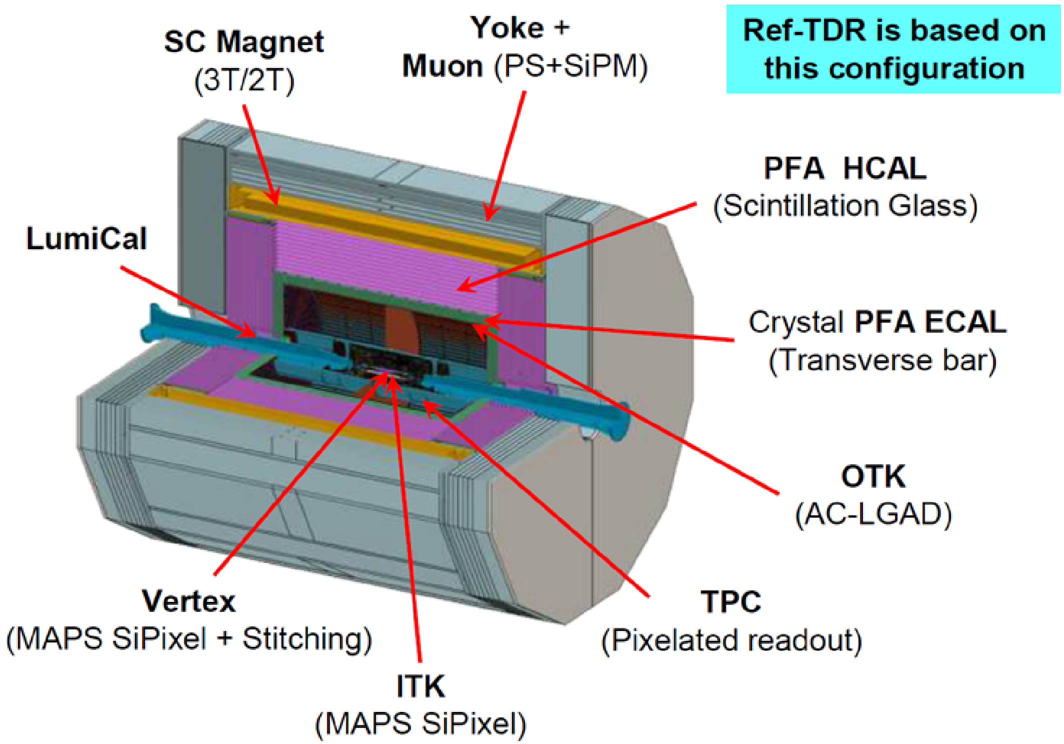
Calibration: Low luminosity Z at 3T
Approximately $10^{35}cm^{-2}s^{-1}$
1%-20% of high luminosity Z





CEPC Detector Progresses

- Design of the CEPC detector and its key specifications have evolved with R&D efforts, taking into account a balance of factors including detector performance, power consumption, cost and construction risks.
- Time Projection Chamber detection technology: extensively explored within the LCTPC/ILD collaboration.
  - Tracking system: Silicon combined with gaseous tracker for the **tracking and PID.**

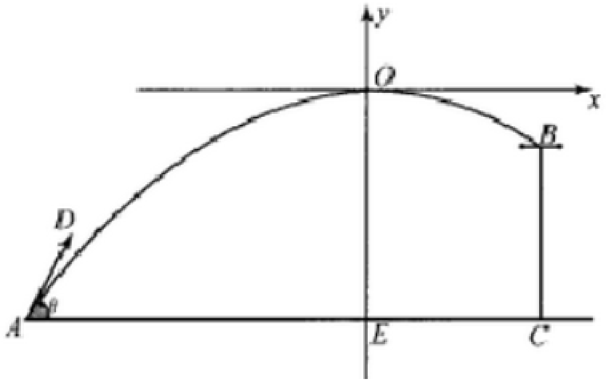


Sub-system	Key technology	Key Specifications
Vertex	6-layer CMOS SPD	$\sigma_{r\phi}$ ~ 3 μm, X/X_0 < 0.15% per layer
Tracking	CMOS SPD ITK, AC-LGAD SSD OTK, TPC + Vertex detector	$\sigma\left(\frac{1}{P_T}\right) \sim 2\times10^{-5} \oplus \frac{1\times10^{-3}}{P\times sin^{3/2}\theta}(GeV^{-1})$
Particle ID	dN/dx measurements by TPC Time of flight by AC-LGAD SSD	Relative uncertainty ~ 3% σ(t) ~ 30 ps
EM calorimeter	High granularity crystal bar PFA calorimeter	EM resolution ~ $3\%/\sqrt{E(GeV)}$ Effective granularity ~ 1×1×2 cm^3
Hadron calorimeter	Scintillation glass PFA hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(GeV)}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(GeV)}$

- **Status of TPC R&D in CEPC TDR stage**

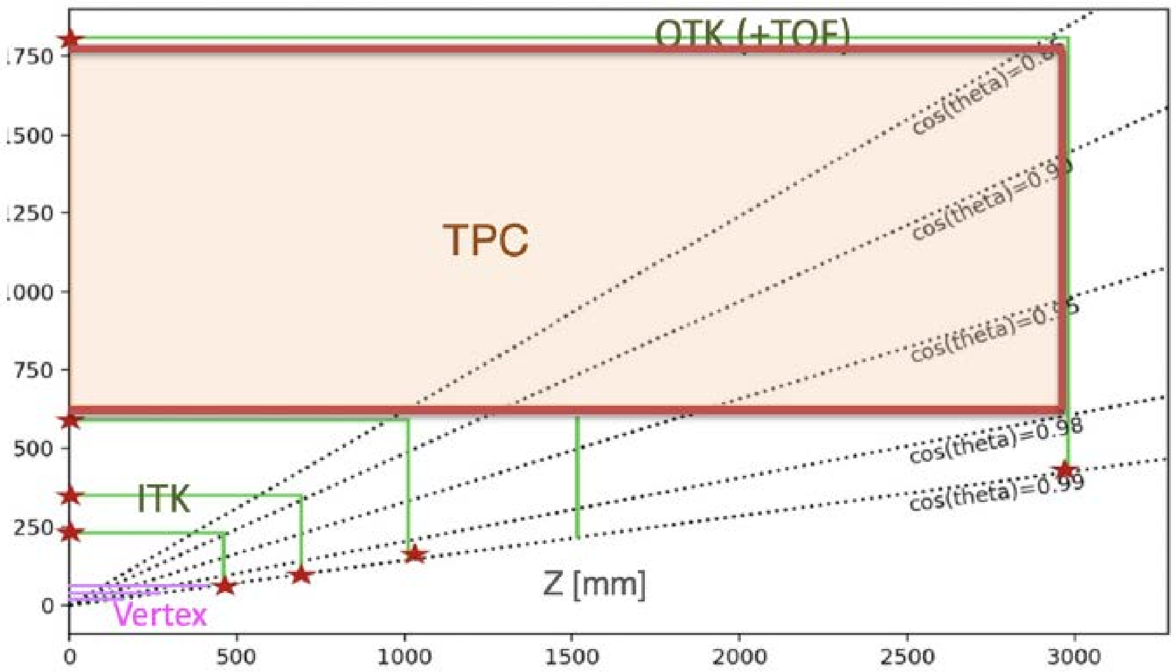
- **NEED a good tracker system?**
    - **Large 3D volume,**
    - **High precision,**
    - **Good reconstruction,**
    - **Easy to handle**

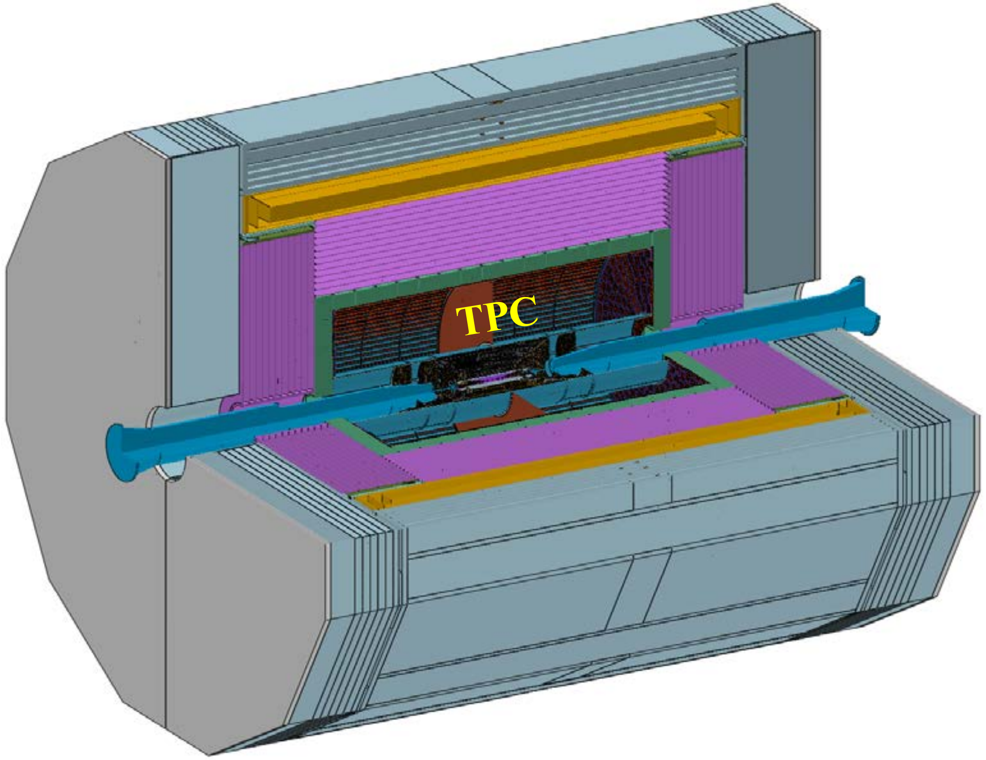
NEED a good tracker system?



Baseline design of TPC technology in CEPC ref-TDR

- Tracking system: Silicon combined with gaseous chamber for the tracking and PID
  - Pixelated readout TPC as the **baseline gaseous detector** in the CEPC ref-TDR
    - Radius of TPC from 0.6 m to 1.8 m, pixelated readout size: 500μm×500μm
    - Ultra light material budget of the barrel and endplate

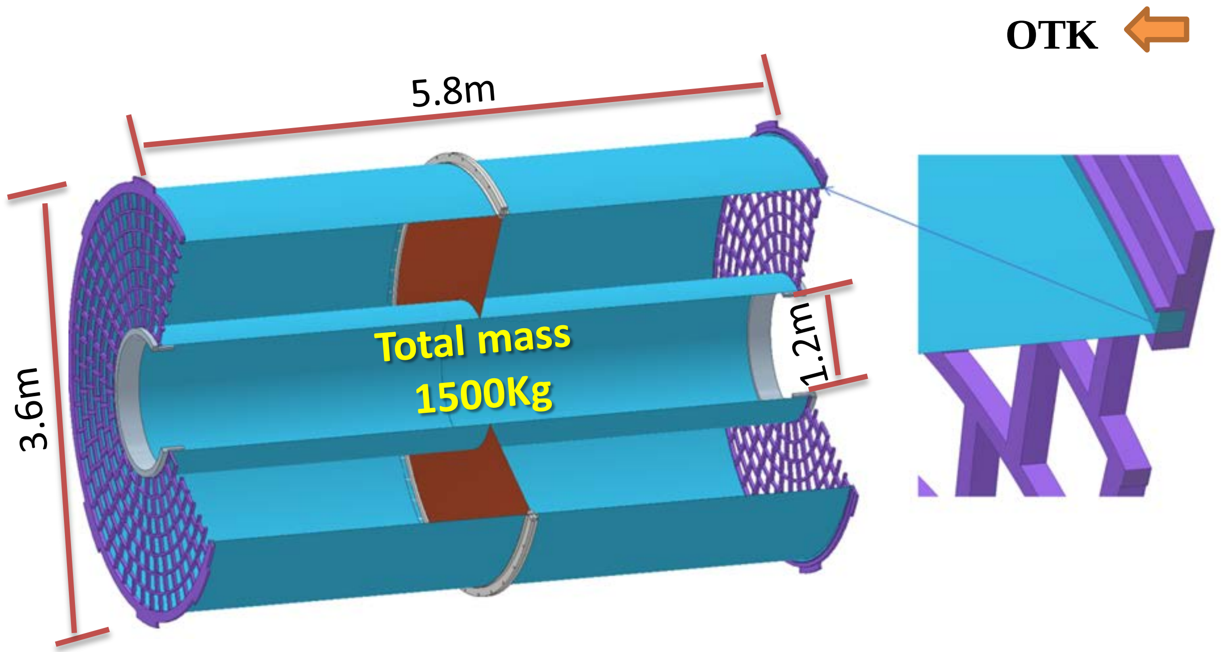


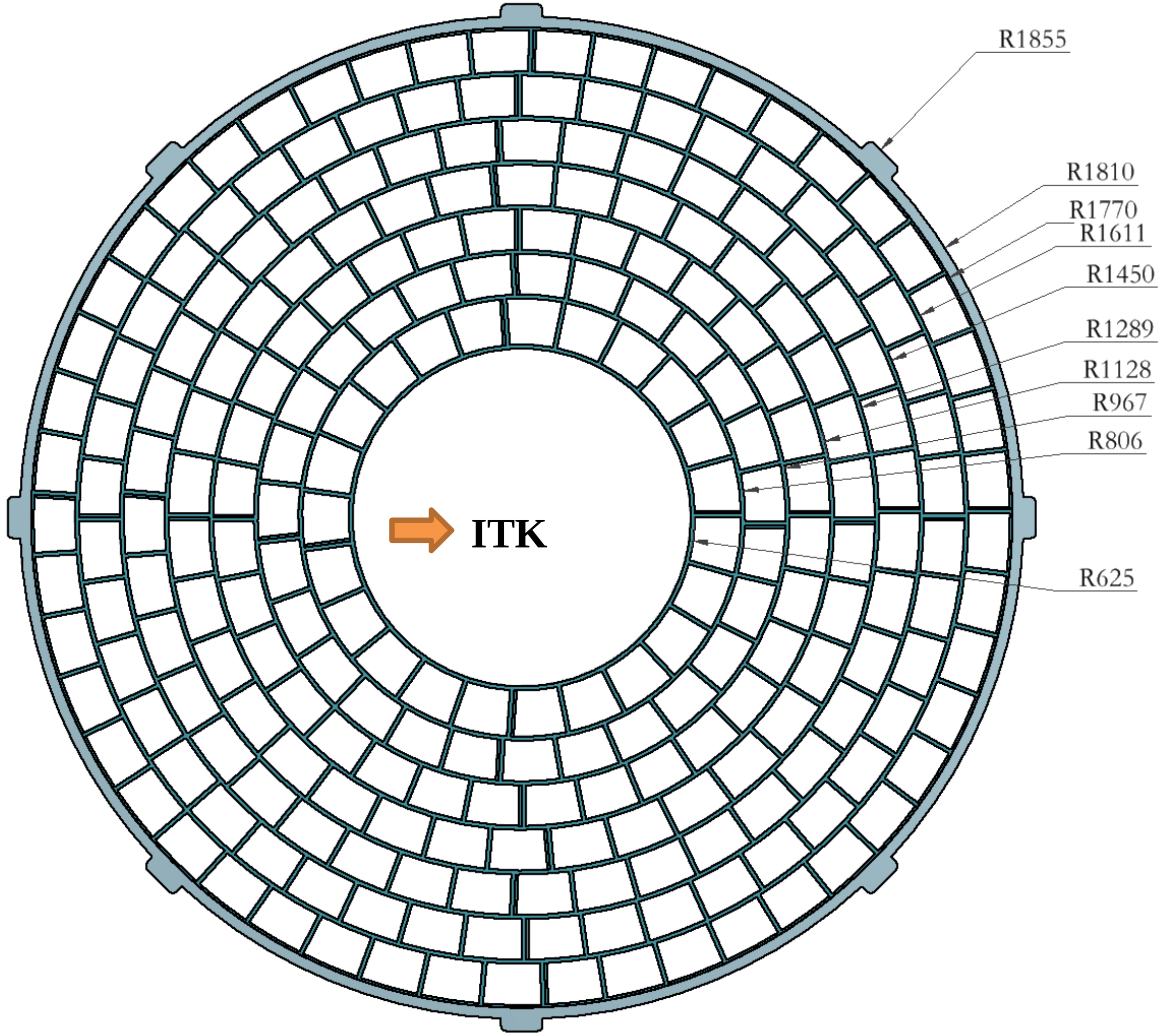


Geometry of the tracking detector system of the CEPC TDR

Parameters of TPC technology in CEPC ref-TDR

TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Module size	206mm×224mm×161mm
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF4/iC4H10=95/3/2
Maximum drift time	34μs @ 2.75m
Detector modules	Pixelated Micromegas

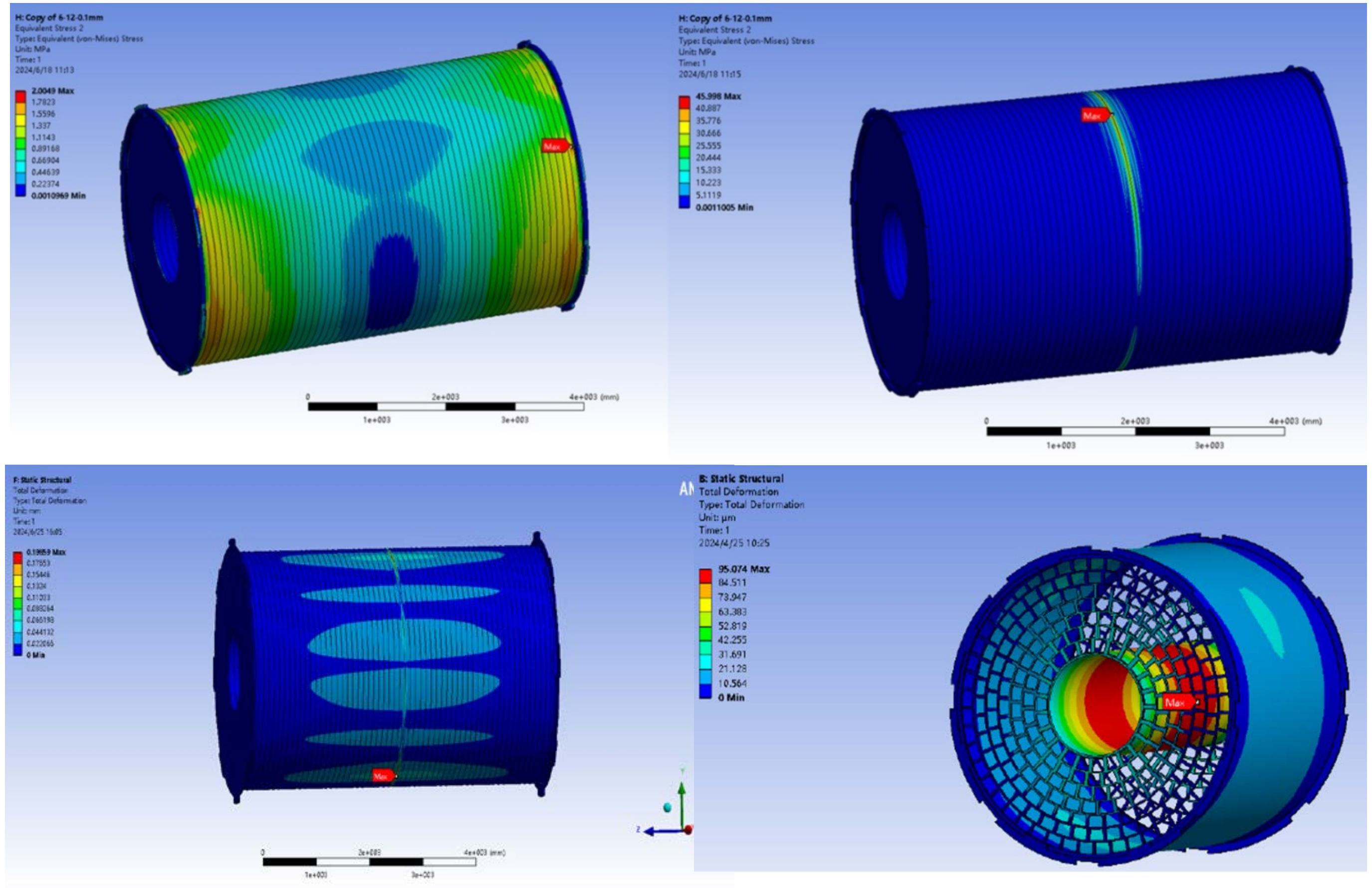




Detailed design of TPC detector in ref-TDR

Ultra-light barrel and FEA analysis

- 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 endplate



Property	Symbol	Units	QM55 Carbon Fiber
Longitudinal Modulus	E1	GPa	303
Transverse Modulus	E2	GPa	333
In-Plane Shear Modulus	G12	GPa	233
Poisson's Ratio	v12	-	0.83
Tensile Strength	Xt	MPa	1610
Compressive Strength	Xc	MPa	800
In-Plane Shear Strength	S	MPa	62
Thermal Expansion Coefficient	α1	Strain/K	-0.7

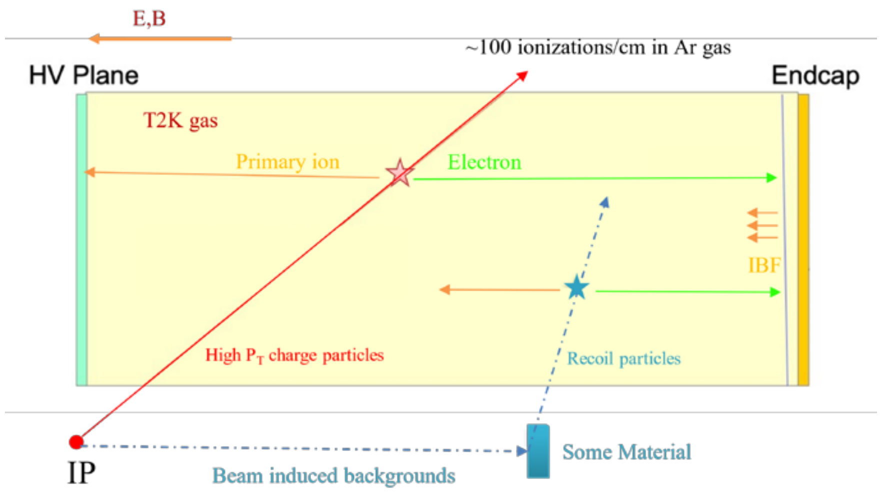
Material budget of TPC barrel

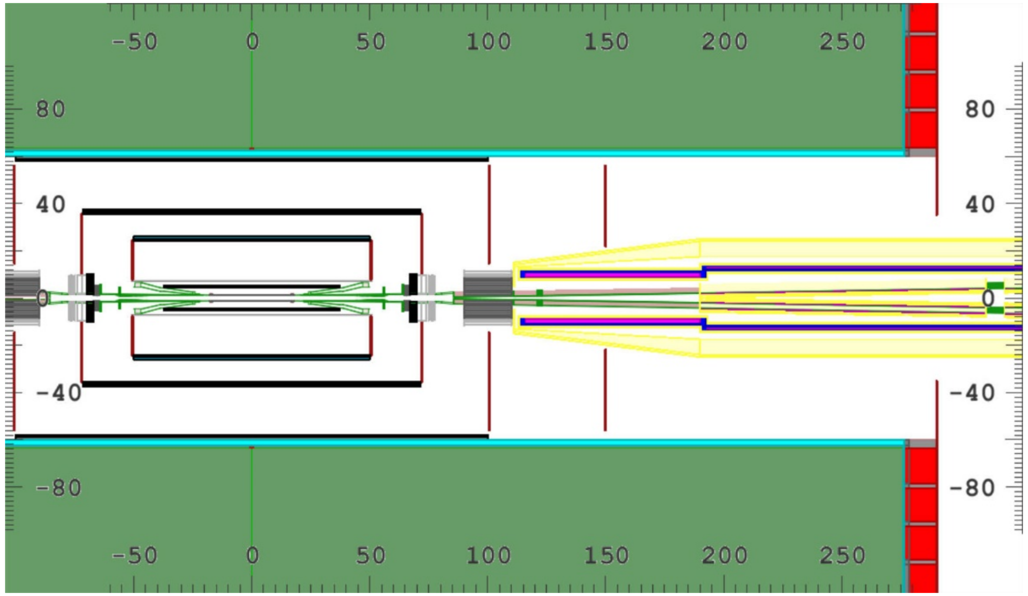
Layer of the barrels	D[cm]	X_0[cm]	d/X_0[%]
Copper shielding	0.001	1.45	0.07
CF outer barrel	0.020	25.28	0.08
Mirror strips	0.003	1.35	0.19
Polyimide substrate	0.005	32.65	0.02
Field strips	0.003	1.35	0.19
CF inner barrel	0.010	25.28	0.04
Sum of the material budget			**0.59**

- **Simulation and prototype preparation**

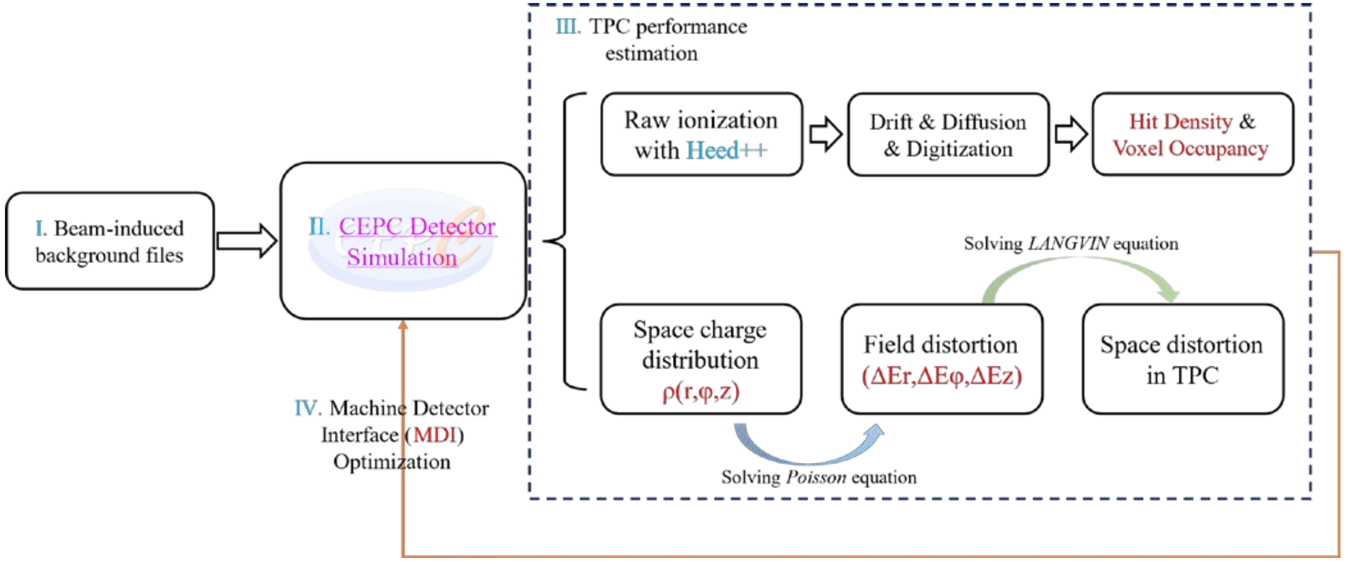
Beam background simulation

- Space charge in TPC chamber
  - Physics events: H→ss/cc/sb, Z→qq…(High P_T)
- Higgs/Z background sources
  - I. Pair production (Luminosity related)
  - II. Single Beam (BGB, BGH,Touschek Scatter…)
  - III. Synchrotron Radiation
  - IV. Injection background





CEPC MDI

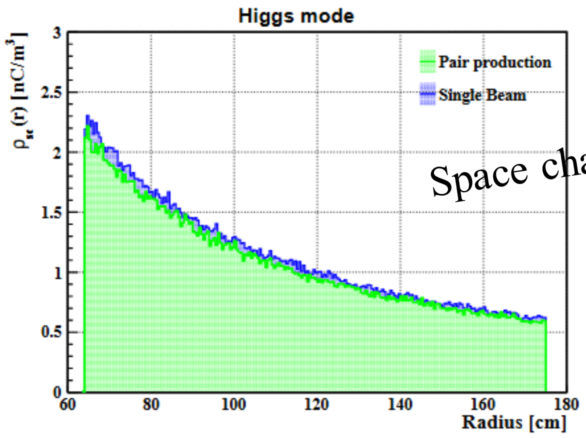


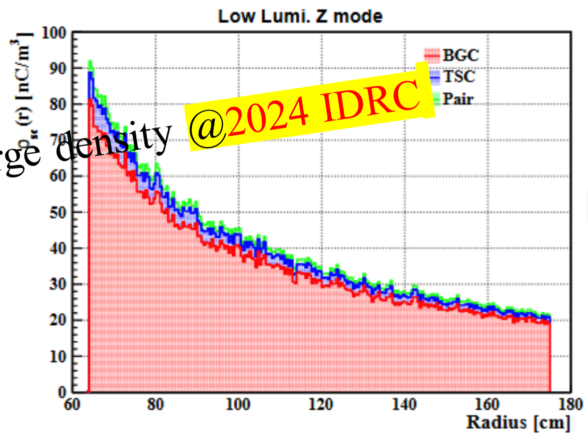
Beam Background Simulation framework of BG for TPC

Space charge density and the beam background

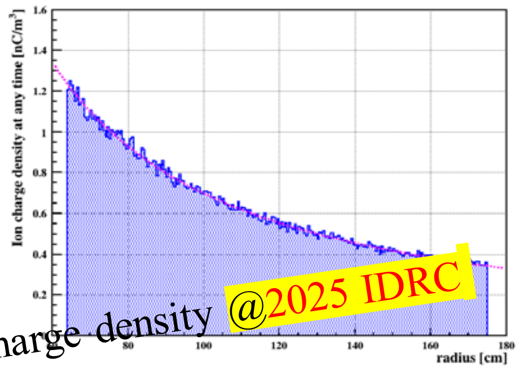
- In the TPC, the space charge is caused by low-energy photons (<10 MeV) from beam background.
  - Pair-production at Higgs and beam-gas interaction BG at Low-Z
- To add shielding, the space charge effects caused by beam background in the TPC are reduced by approximately two orders of magnitude.
  - Added Collimators ×1/5 ~ 1/10 for LowLumi. Z mode
  - LumiCal shielding ×1/2
  - Stainless steel shielding outside the beam pipe cryostat ×1/2 ~1/4

IBF×Gain~1 primary ion level





Space charge density @2024 IDRC



Space charge density @2025 IDRC

Table 6.5: TPC space charge distortion estimation at CEPC Higgs and low luminosity Z run. The average space charge density of ALICE TPC is about 120 nC/m^3.

Mode	Space charge density (steady)	Remark	Optimization strategy
Higgs	$\rho_{sc0} \sim 0.04$nC/m^3 (Max. distortion: 12 μm)	w.o. low energy photons (<10 MeV) contribution	Acceptable
Higgs	$\rho_{sc1} \sim 30\times\rho_{sc0}$	w. low energy photons (<10 MeV) contribution	Analysis initial position distribution of low energy photons and add more shielding
low lumi. Z	$\rho_{sc2} \sim 0.62$nC/m^3 (Max. distortion: 150 μm)	w.o. low energy photons (<10 MeV) contribution	Acceptable in most of TPC region
low lumi. Z	$\rho_{sc3} \sim 40\times\rho_{sc0}$	w. low energy photons (<10 MeV) contribution	Shielding and developing a dedicated distortion correction algorithm

Distortion in TPC at Higgs/Low luminosity Z @3T

- Radial distortion (Δ_r) is much smaller than azimuthal distortion, almost imperceptible when along the track for most P_T track

IBF×Gain=1, same primary ion level

  - Azimuthal distortion ($\Delta_{r\varphi}$) has much serous impact both on high/low P_T tracks
  - The maximum $\Delta_{r\varphi}$ is $10\mu m$@Higgs (**acceptable**)
  - The maximum $\Delta_{r\varphi}$ can be reduced to $<150\mu m$@Z (**optimization of MDI**)Including Pair + Single Beam

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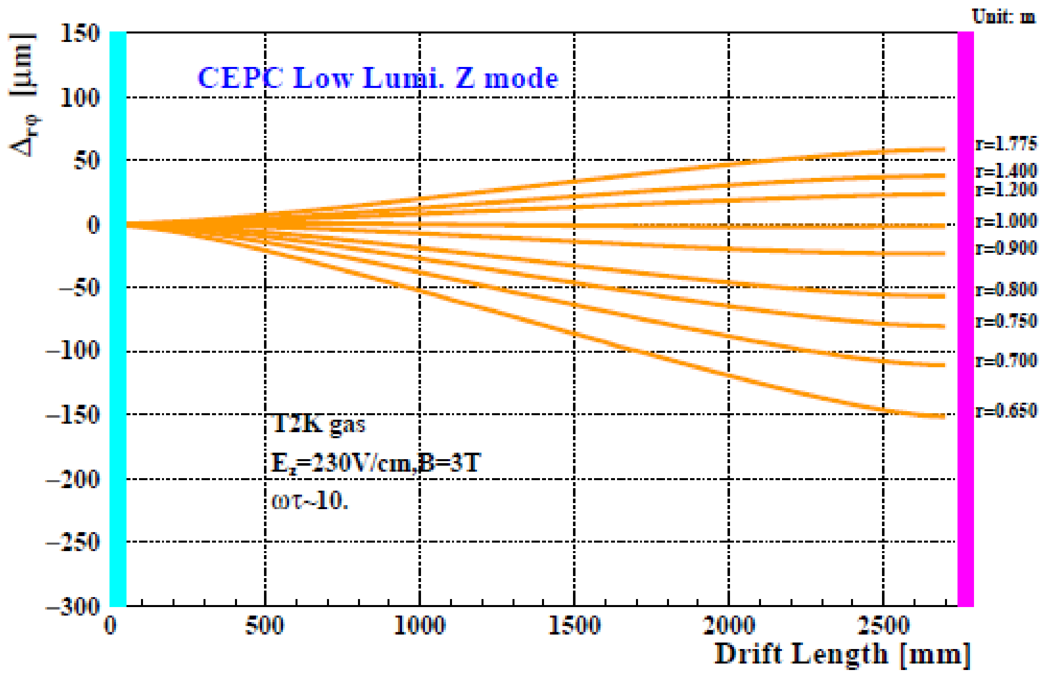
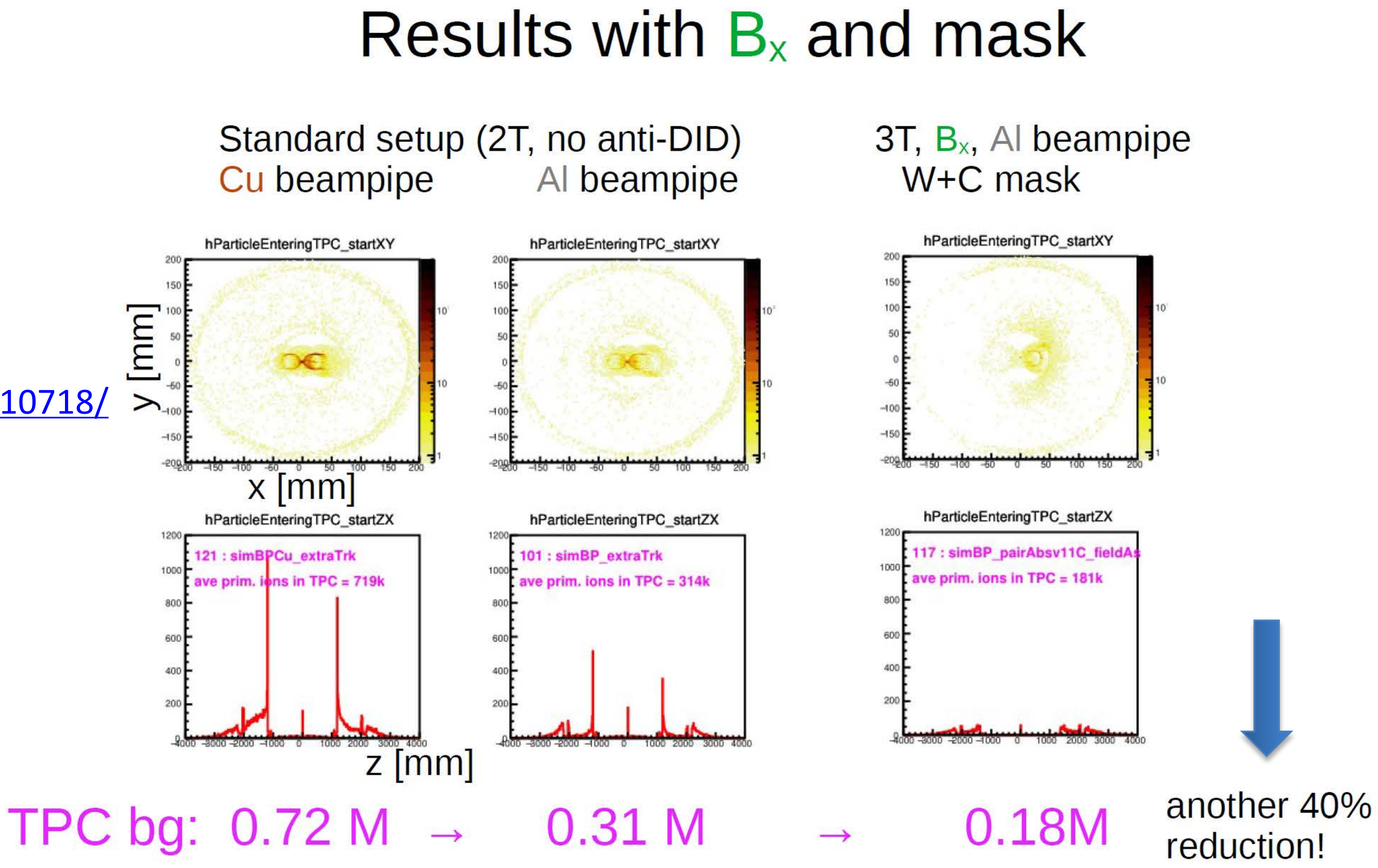


Some collaboration with FCCee and ILD

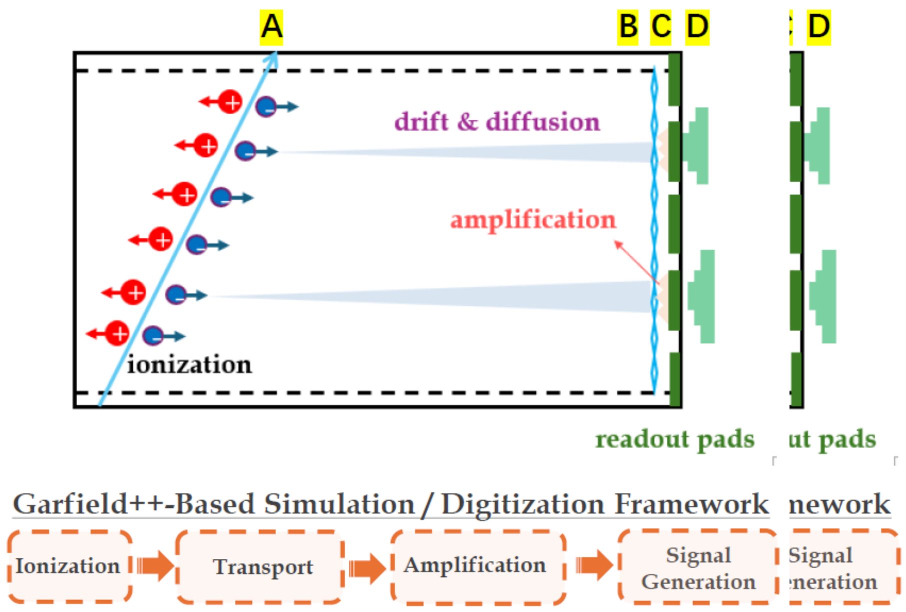
- Try to minimize beamstrahlung BG using Bx and mask shielding.
  - Pair-production at Higgs and beam-gas interaction BG at Low-Z

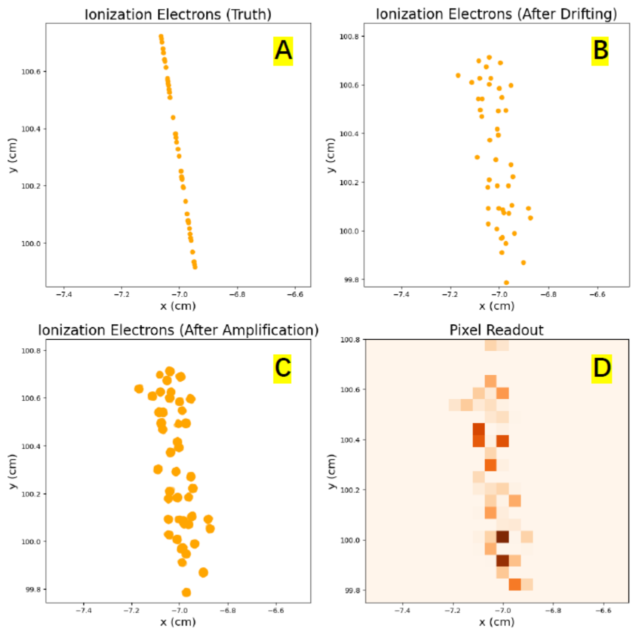


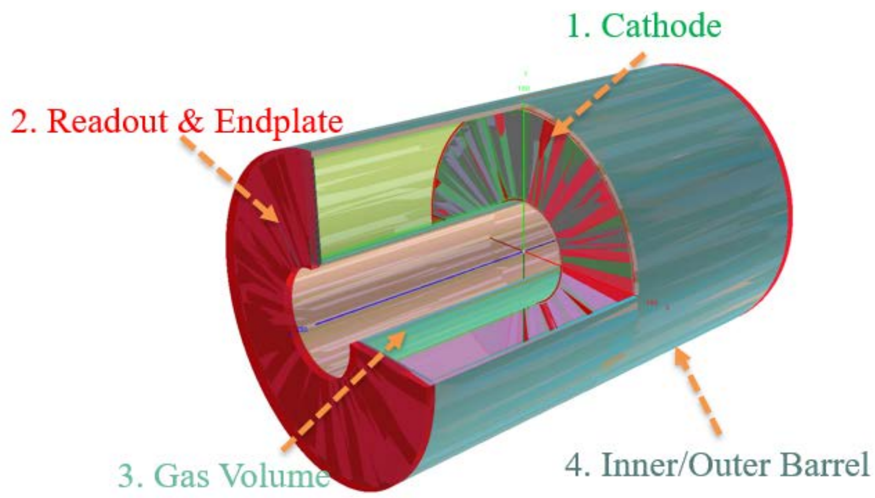
https://agenda.linearcollider.org/event/10718/
Daniel, KEK

Full Simulation of Pixelated readout TPC – Framework

- Sophisticated software for simulation/digitization/reconstruction
  - Geometry implementation based on CEPC Ref-TDR
    - Cathode, Micromegas readout and endplate, barrel, gas volume
  - PID with dn/dx
    - Garfield++-based full simulation/digitization
    - Improved reconstruction based on truncated mean of pixels
  - Tracking: Reconstruction with parameterized hit resolutions



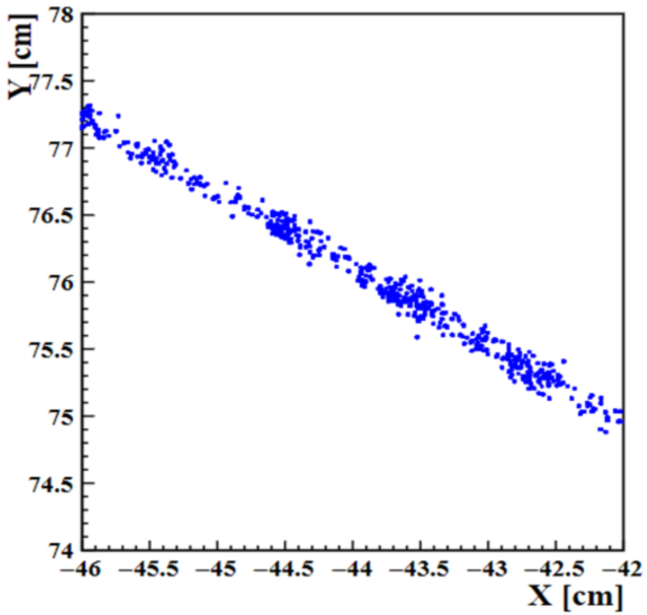




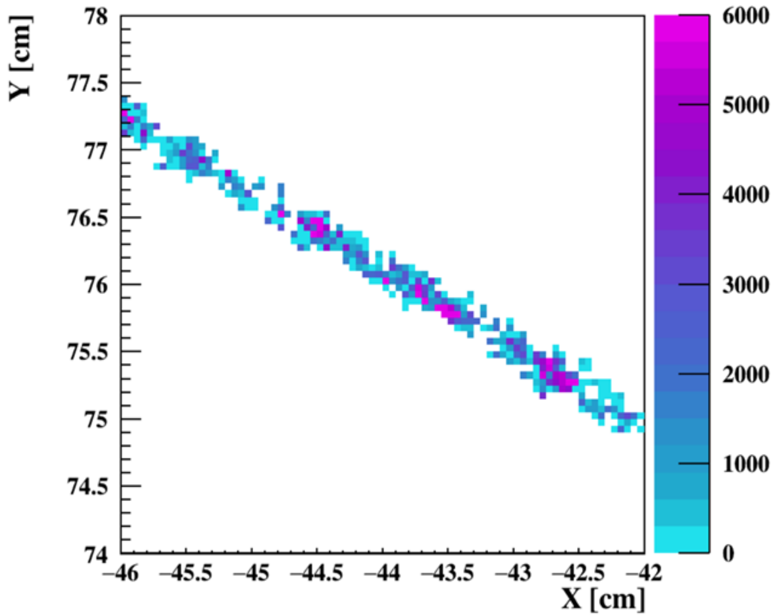
Simulation of TPC detector under 3T and T2K mixture gas

Full Simulation of Pixelated readout TPC – Readout size

- Simulation results showed that readout size can be optimized at around 500μm.
  - Optimization started in this ref-TDR to meet Higgs/Z at 3T
  - Focused on **100mW/cm^2 and 500μm readout** for ref-TDR (<12kW/endplate, Water cooling option)
- TPX3/4 (55×55μm^2, 110×110μm^2) readout TPC prototype has been validation on DESY beams.
  - Power consumption: 2W/cm^2 ; Low power mode: 1W/cm^2 (**high power consumption!**)

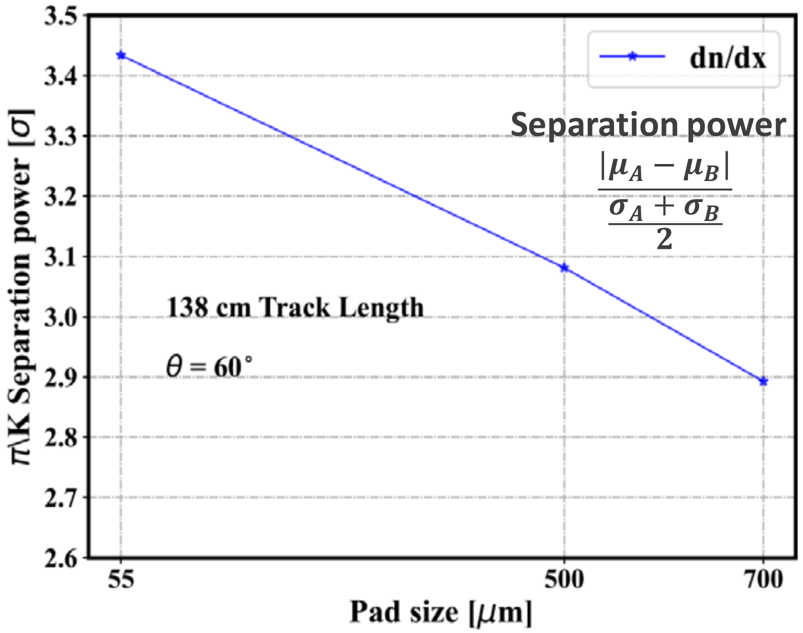


pixel response (55 μm× 55 μm)



pixel response (500 μm× 500 μm)

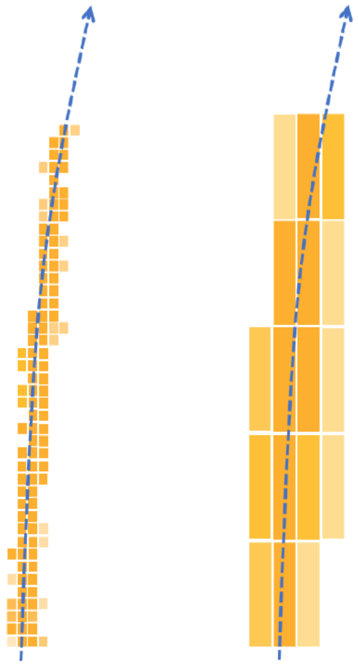
Lx



Optimization of readout size. Balancing of performance and cost power consumption, etc.

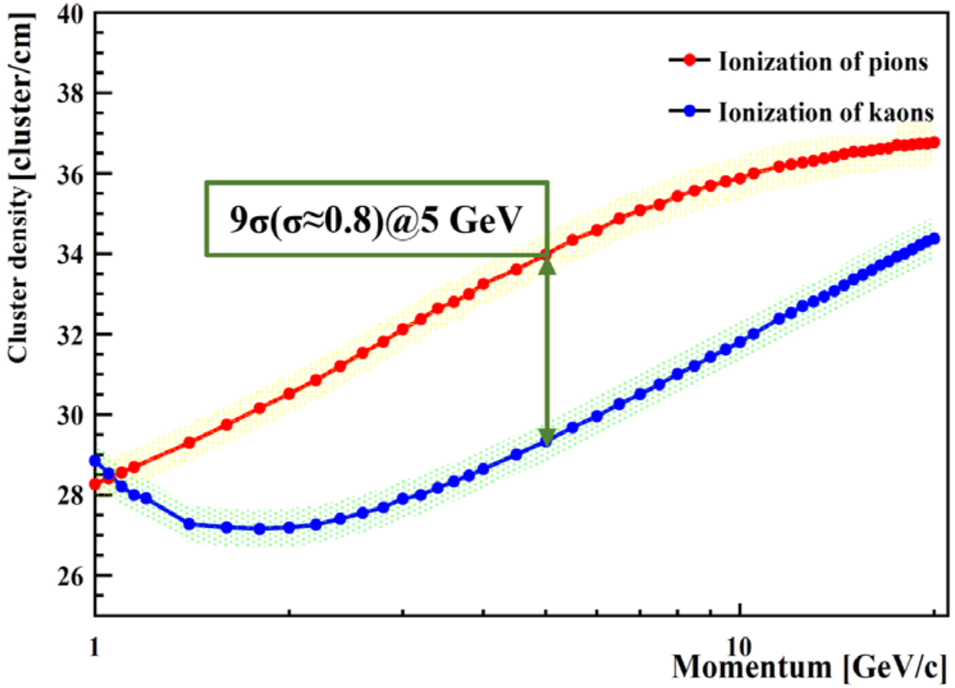
Full Simulation of Pixelated readout TPC – PID with dn/dx

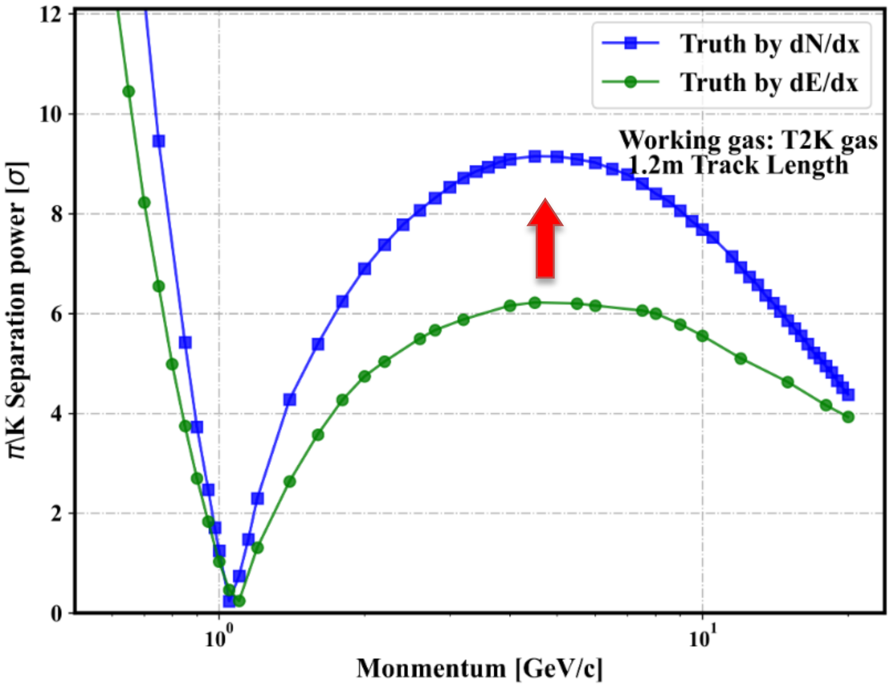
- dn/dx: Count the number of pixels with small-pixel-size readout
- dE/dx: Measure the total energy loss
  - dn/dx has much better PID by getting rid of fluctuations from energy deposition and amplification



500 x 500 μm^2 Readout size

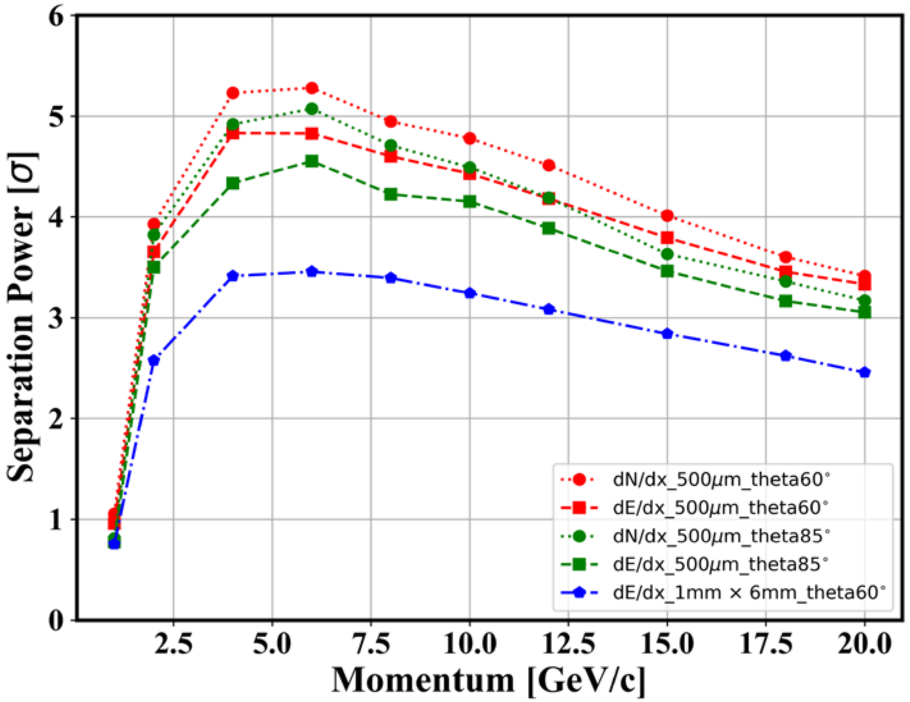
1x6 mm^2 Pad

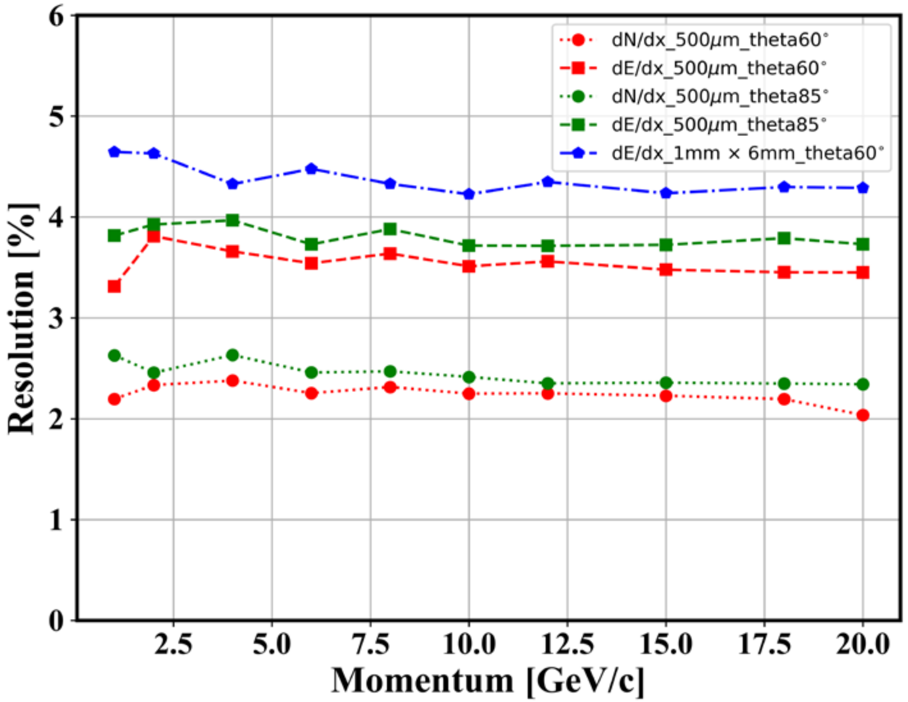




Full Simulation of Pixelated readout TPC - PID Performance

- Updated dn/dx reconstruction (+20% improvement than previous results)
  - Layer grouping: Combining pixel readout units into layers
  - Pixel counting: Counting pixels with charges above a threshold and normalizing by the track length in each layer (dn/dx per layer)
  - **Much better PID with dn/dx than the traditional dE/dx**

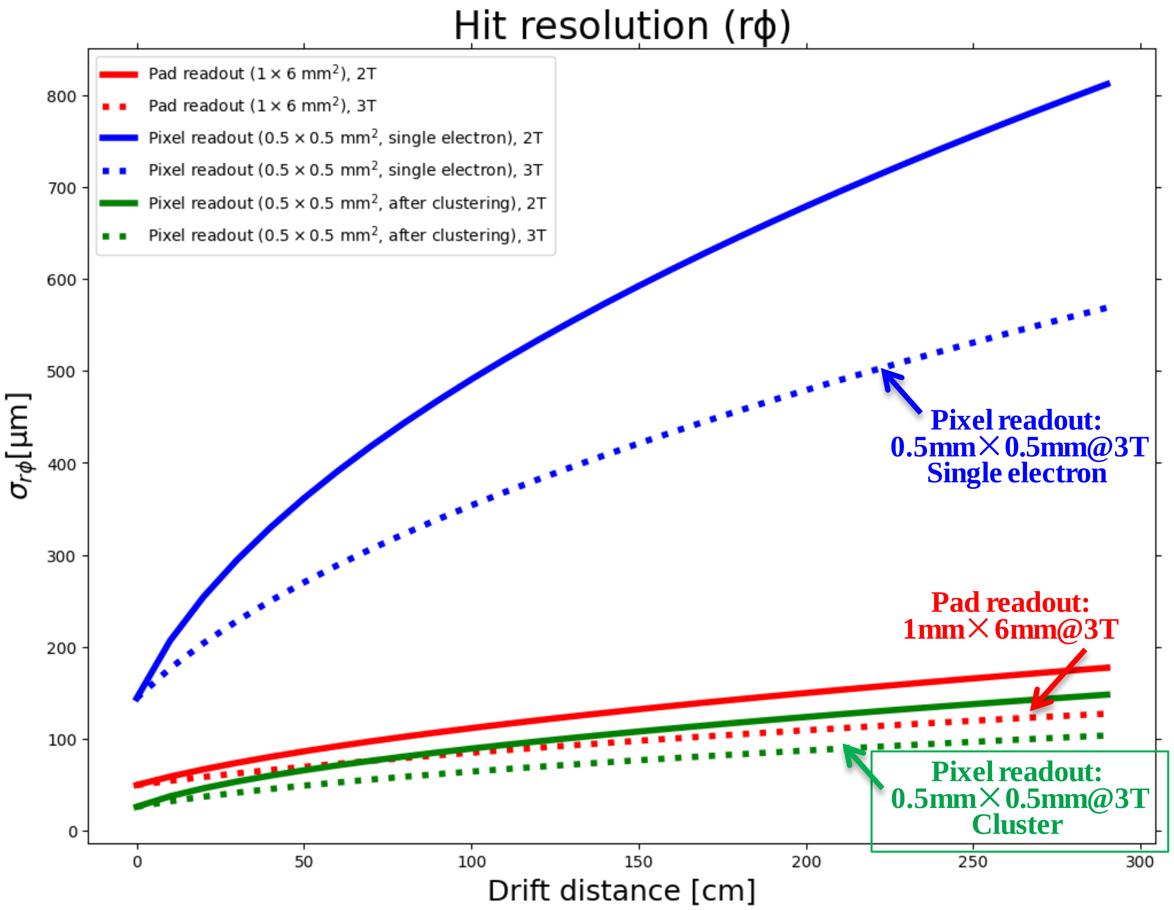


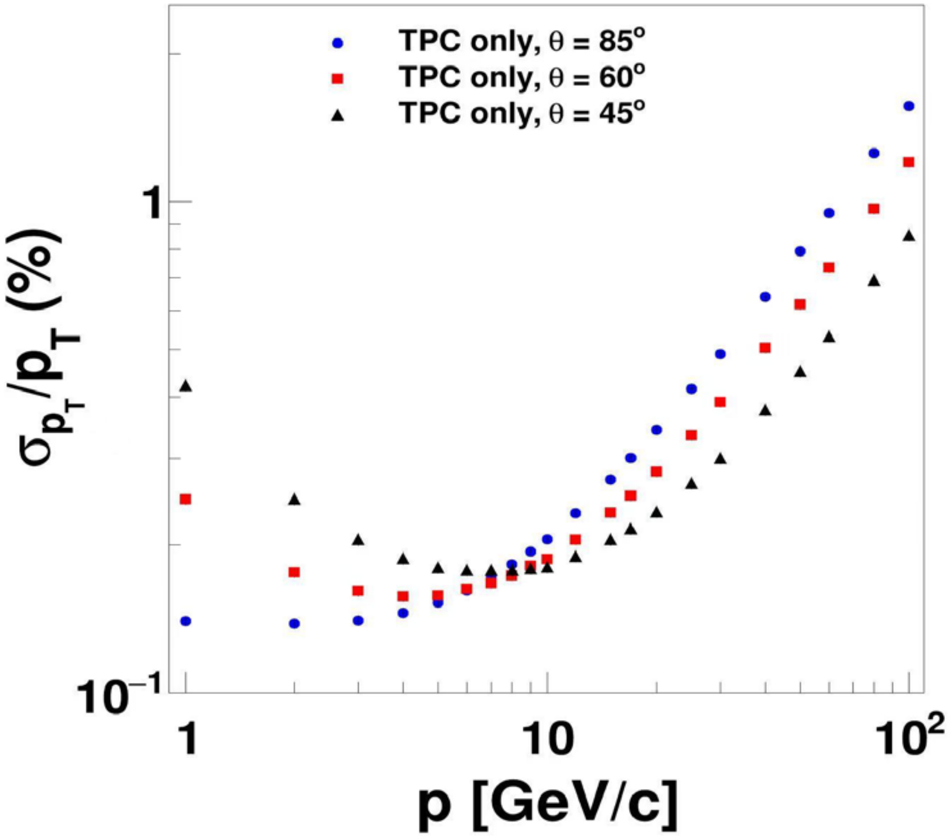


Full Simulation of Pixelated readout TPC – Spatial resolution

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

- The granularity readout and the transverse diffusion are also taken into consideration..
- Tracking with parameterized hit spatial resolutions.

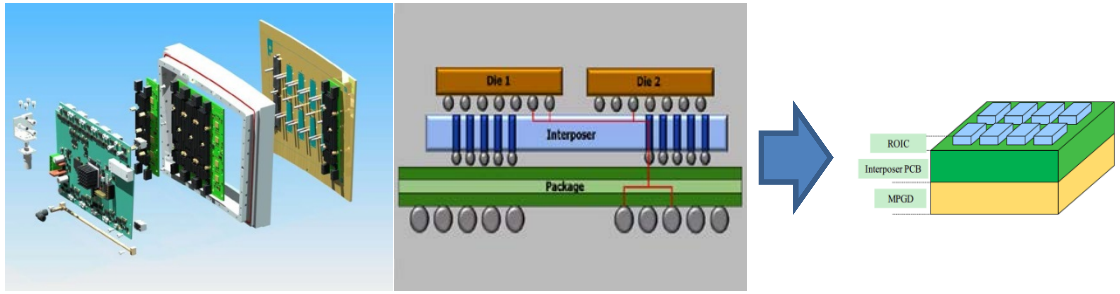


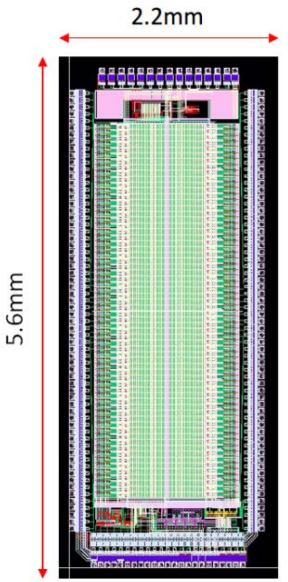


Full Simulation of Pixelated readout TPC – TEPix with 500μm×500μm

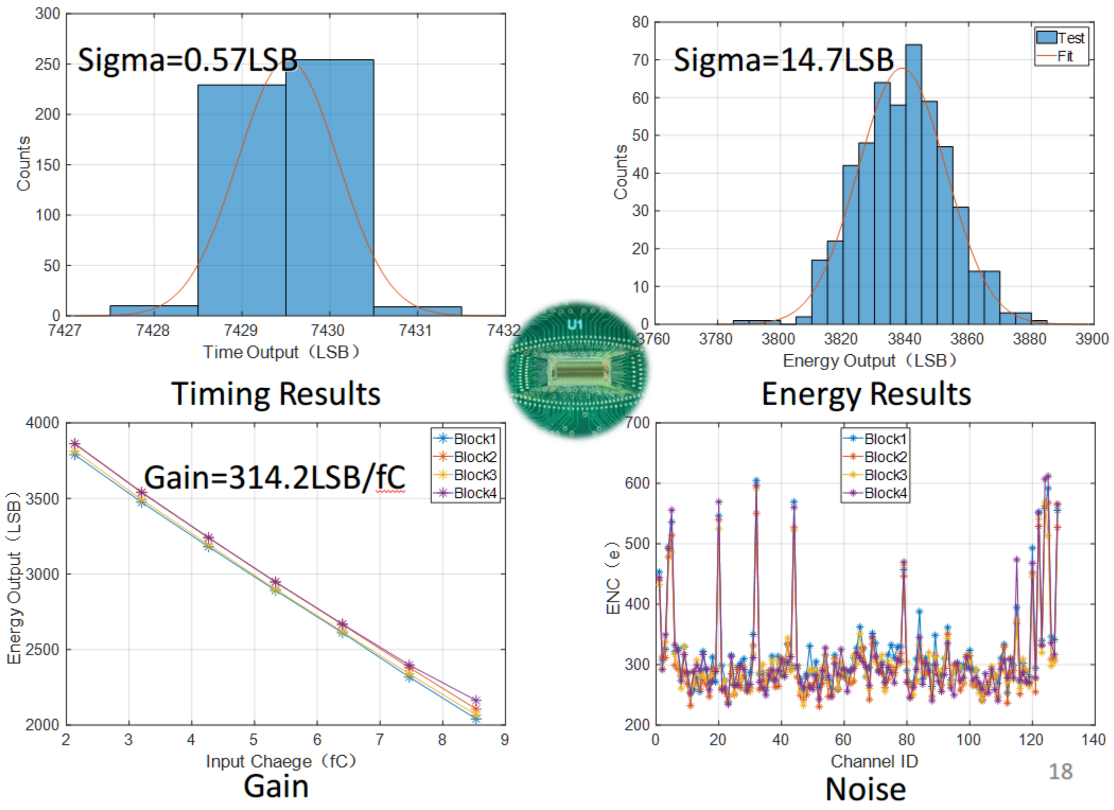
- Pixelated Readout Electronics: TEPix development
  - Multi-ROIC chips + Interposer PCB
  - 180nm Chips
- TEPix: Low power Energy/Timing measurement
  - Low power consumption
  - Timing: 1 LSB(<10ns)
  - Noise: 300e- (high gain)

~ 200mW/cm²
100mW/cm²@65nm





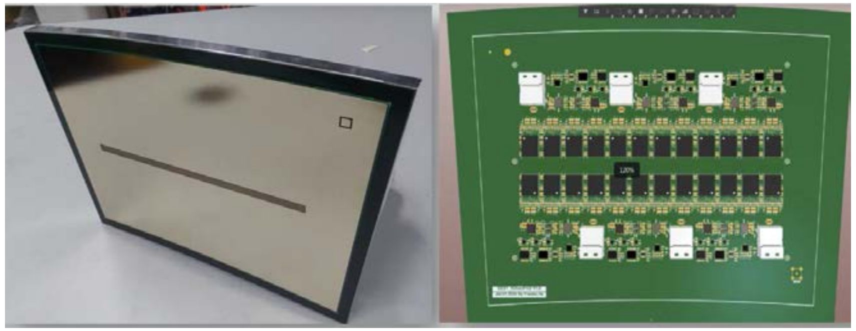
Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns

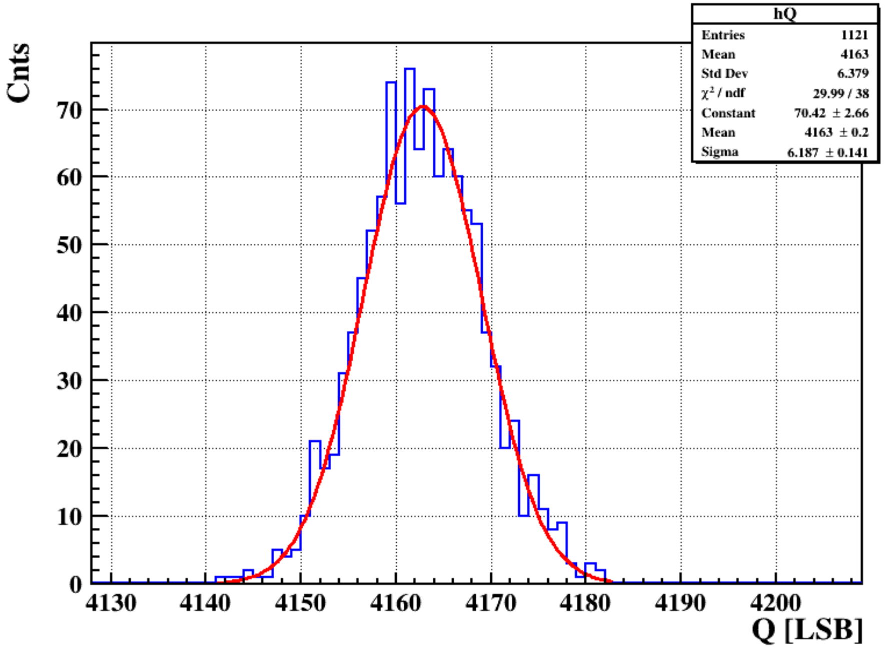


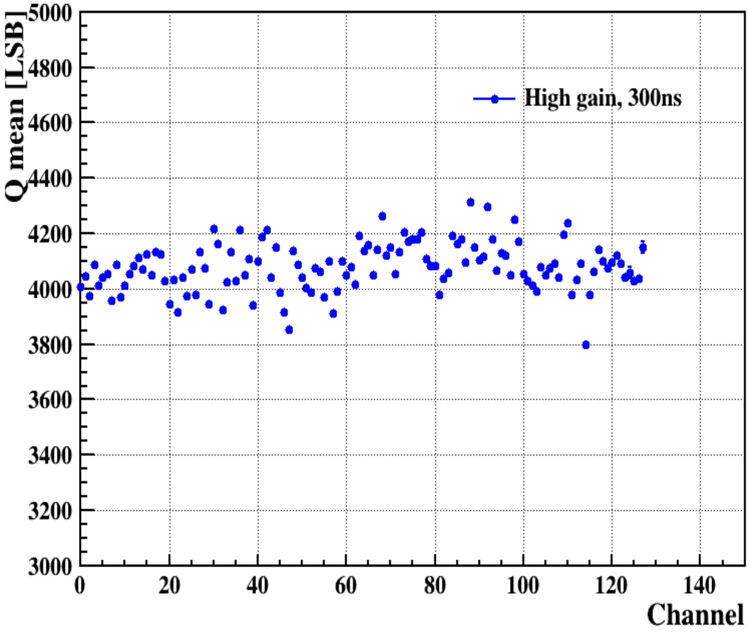
FEE ASIC: TEPIX—Test Results in May

Validation and commissioning of TPC prototype

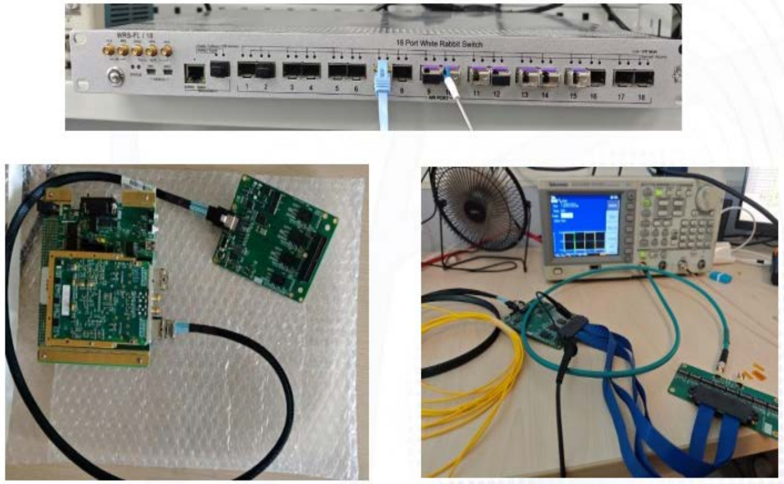
- R&D on Pixelated TPC readout for CEPC TDR.
  - ASIC chip developed and **2nd prototype wafer has been done** and tested.
- Energy/Time value of the channels according to the charged injected
  - The uniformity test result of single TEPIX chip : <5%
- A TPC readout module has developed with 10×300 readout channels (24 TEPIX chips) for the beam test at DESY in November.





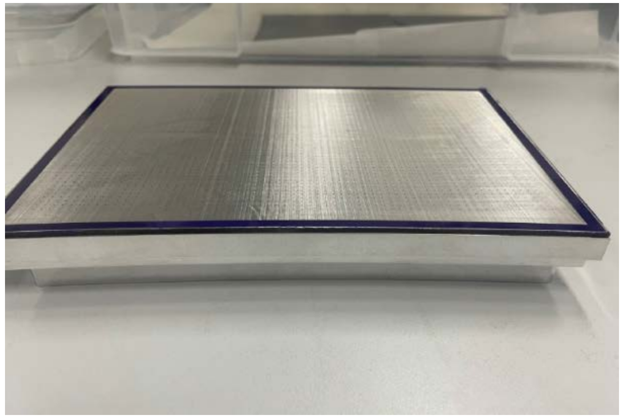


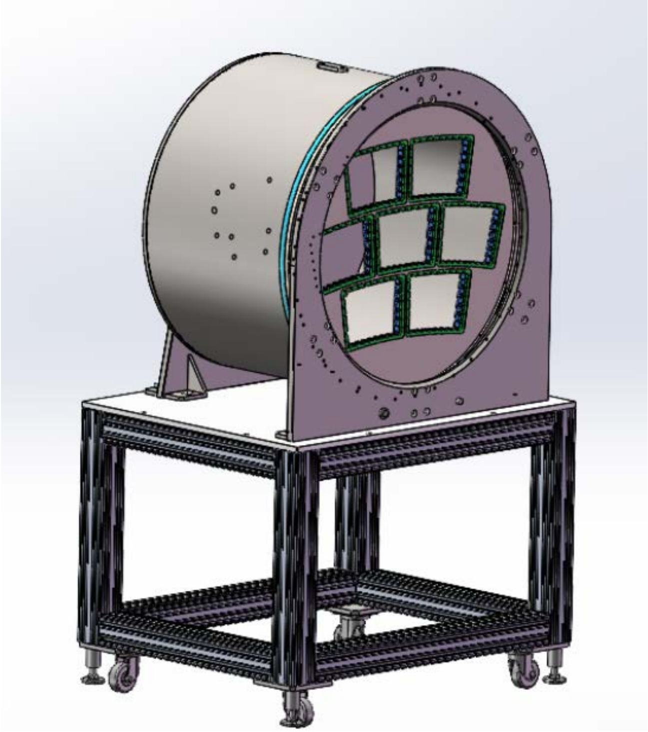
Energy distribution result of TEPIX chip



Work plan of TPC R&D

- Short term work plan (**before September, 2025**)
  - Optimization of TPC detector for CEPC ref-TDR
  - Prototyping R&D and validation with the test beam
    - mechanics, manufacturing, beam test, full drift length prototype
  - Performance of the simulation and Machine Learning algorithm
- Long term work plan (**next 3-5 years**)
  - Development of TPC prototype with low power consumption FEE
    - Collaboration with LCTPC collaboration on beam test
  - Development of the full drift length prototype
    - Drift velocity. Attachment coefficient, T/L Diffusion, etc.





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

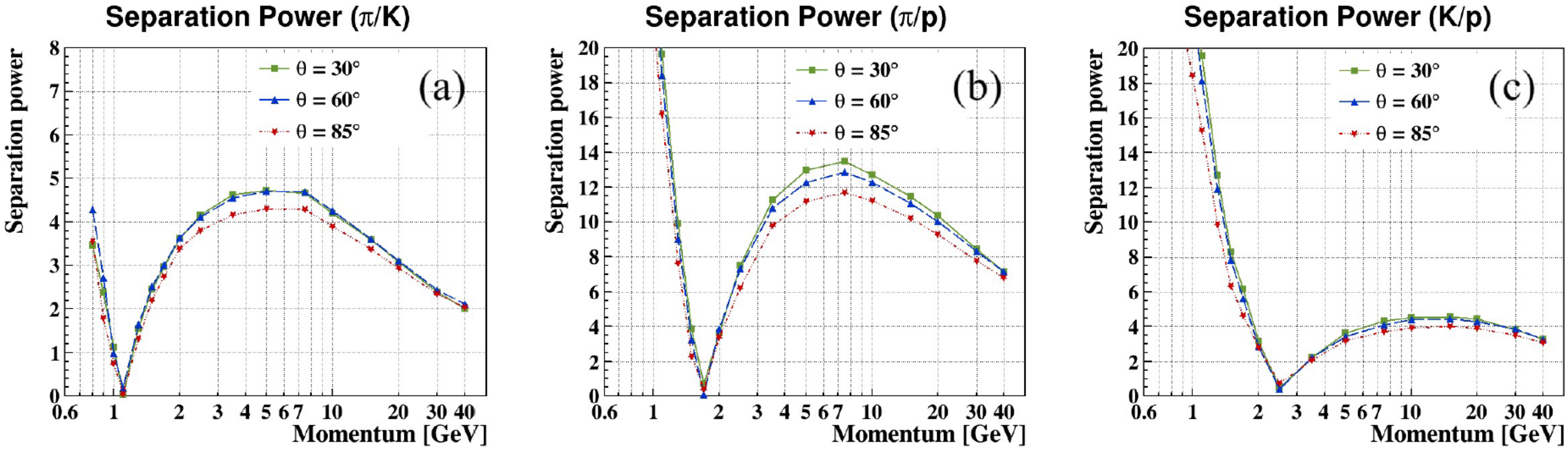
Summary

- 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.
    - Aiming to Higgs and low luminosity Z run at future e+e- collider
    - Radius of TPC from 0.6 m to 1.8 m, readout size 500μm x 500μm
    - Ultra light material budget of the barrel and endplate
    - dn/dx has much better PID by getting rid of fluctuations from energy deposition and amplification
    - π/K: ~3σ @ 20 GeV/c, ~2σ @ 40 GeV/c
    - Beam-induced backgrounds studied based on Garfield++ and CEPCSW
    - Some validation of TPC prototype have been studies using TEPIX
- All inputs to reference detector TDR, planning the short and long term R&D activates
- Synergies with CEPC/LCTPC/FCCee allow us to continue R&D and ongoing. Team actively involved in the international collaborations.

Many thanks!

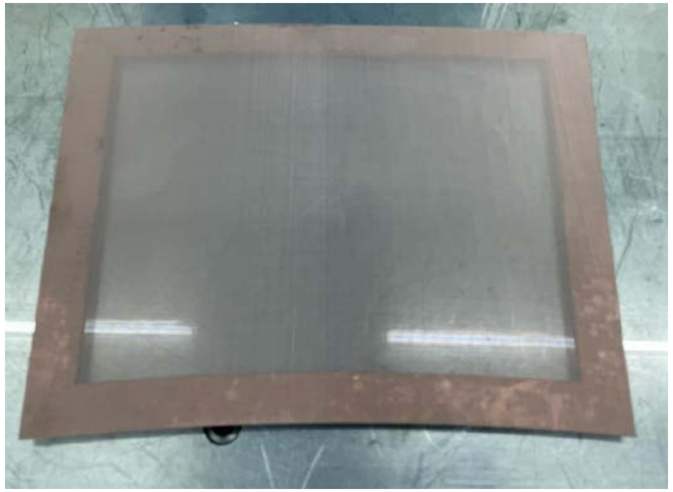
Full Simulation of Pixelated readout TPC – PID performance

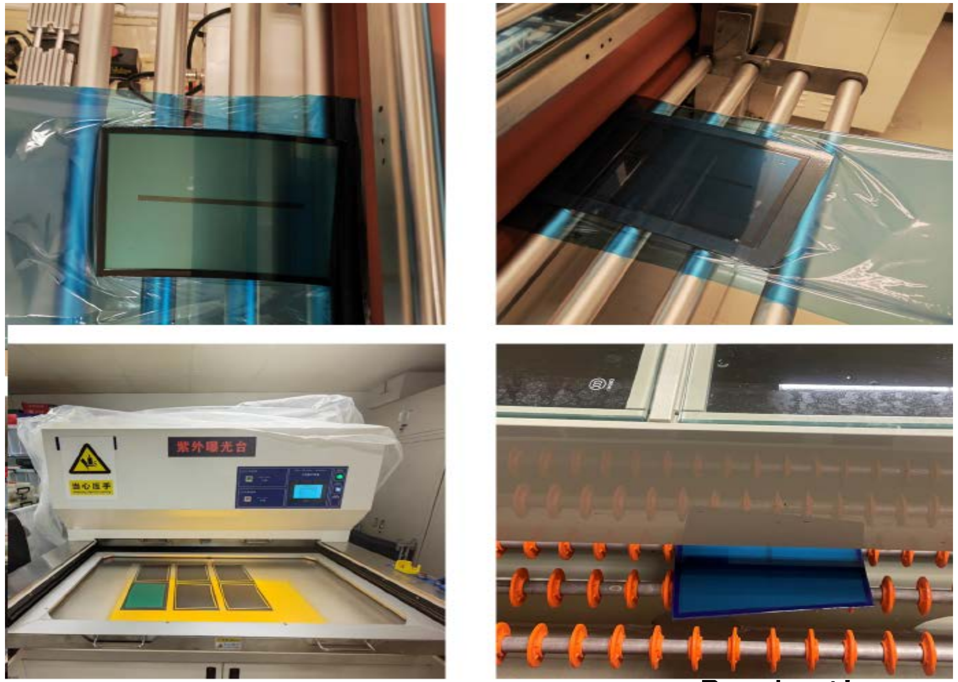
- Performance of the pixelated readout TPC
  - Simulation of π/K, π/p, and K/p separation power with varying momentum and cosθ
  - 30°, 60° and 85°

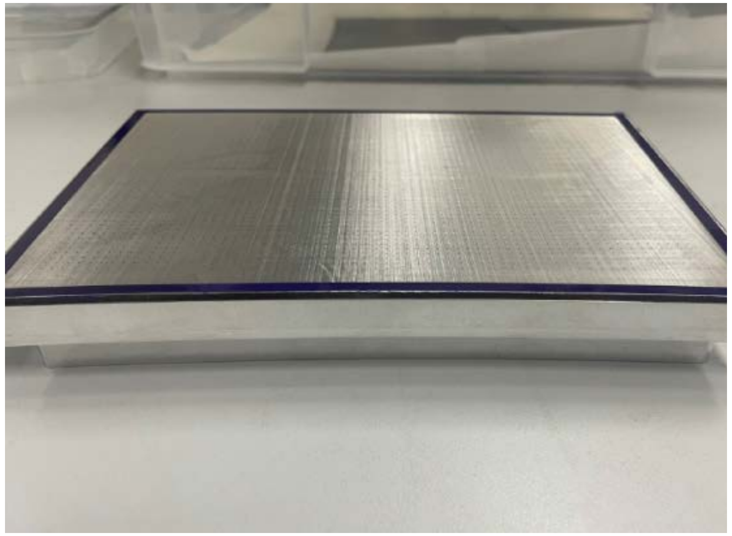


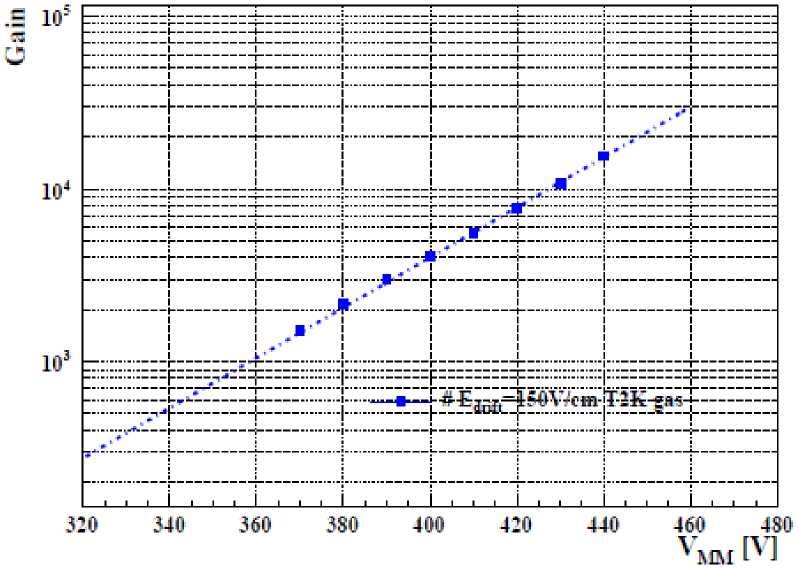
Production of TPC modules

- Development of the Micromegas detector
  - Production in the gaseous detector lab at IHEP
  - Gerber file to film plate (1μm precision)
  - Height of the pillar: 100μm
  - Gain test in working gas



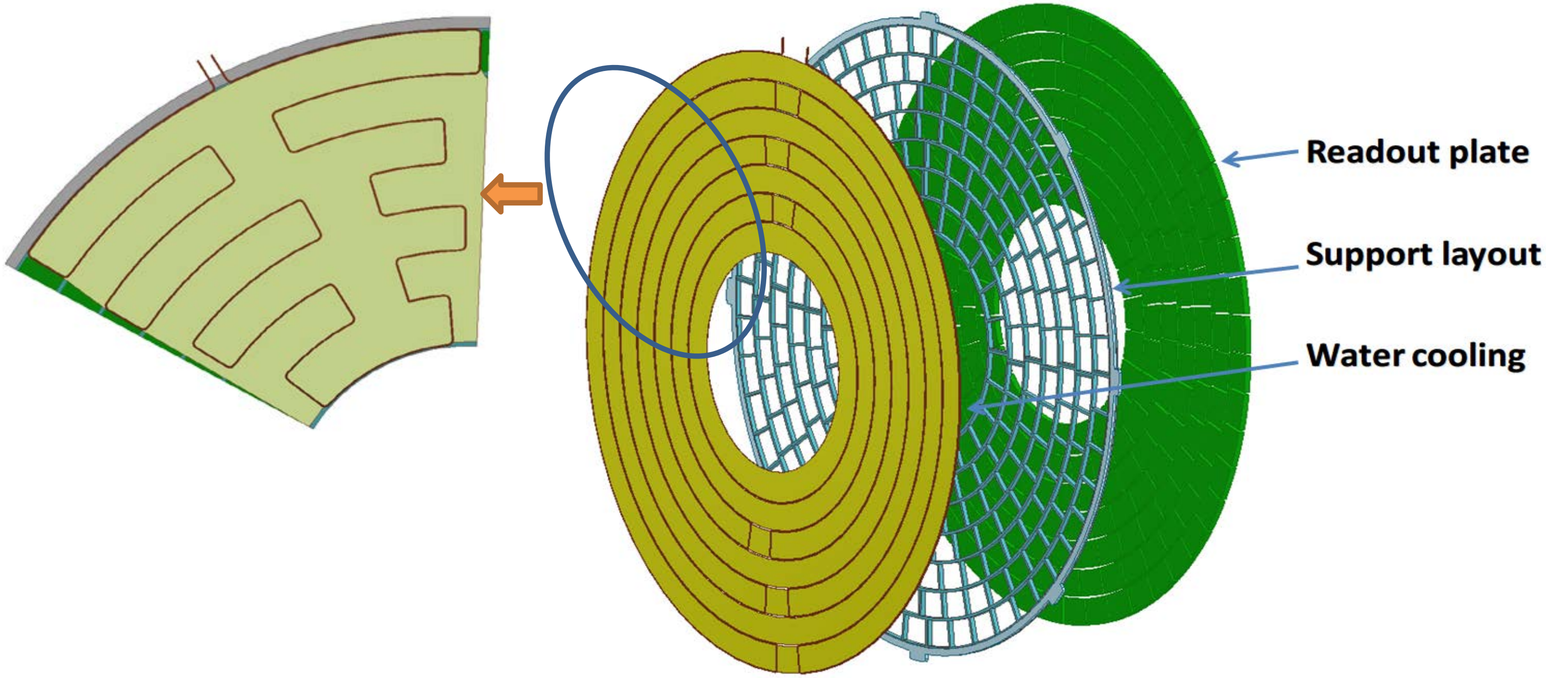






Production and the gain of the detector module

Design of water cooling system



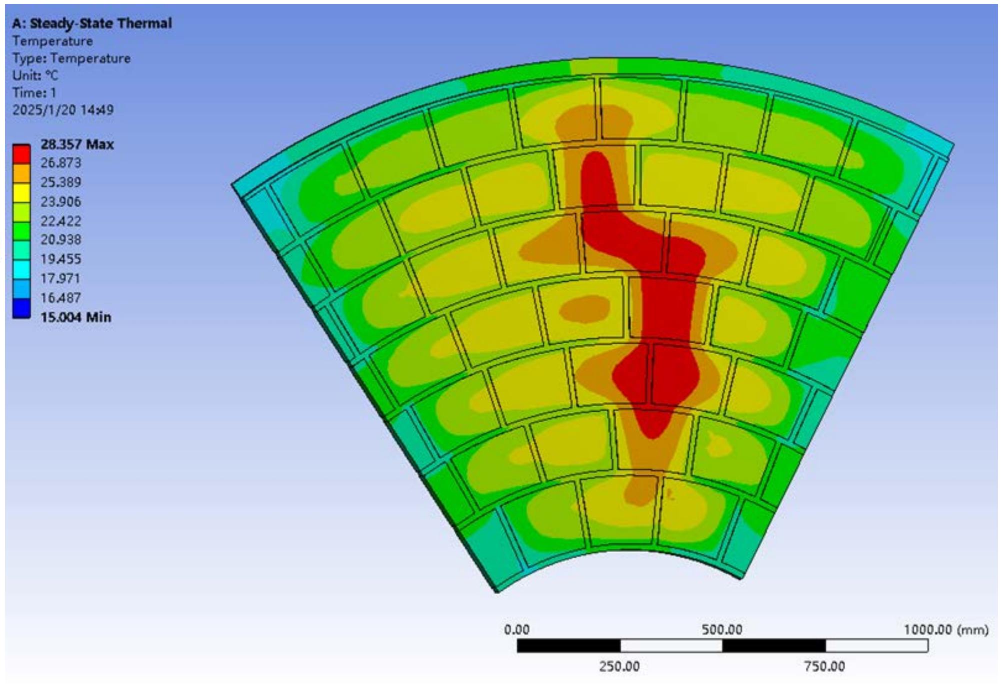


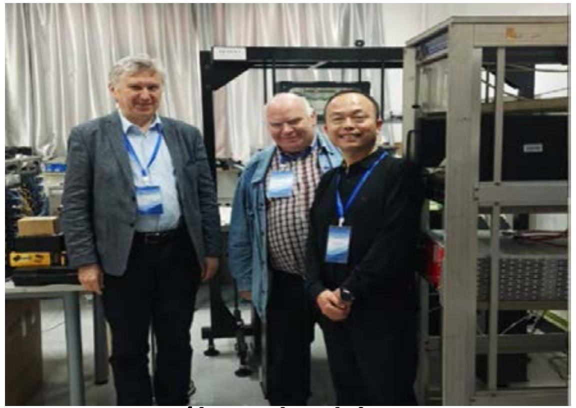
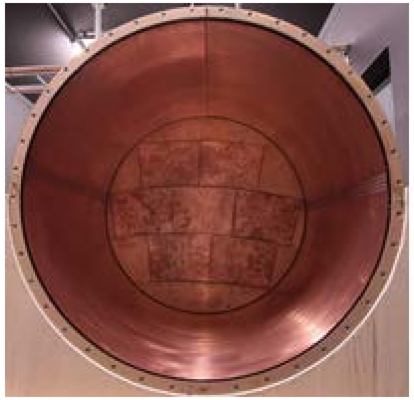
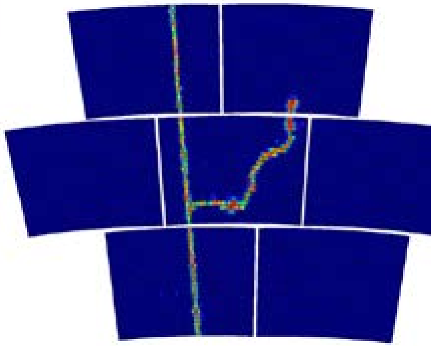
Figure 6.30:

- Static thermodynamic finite element analysis
  - Thermal power average heating power 12kW per endplate
  - Water-cooled tube heat exchange is 5kW/m^2
  - Requirements: **Minimum flow rate is 2.63m/s, flow rate 3.1L/min**.

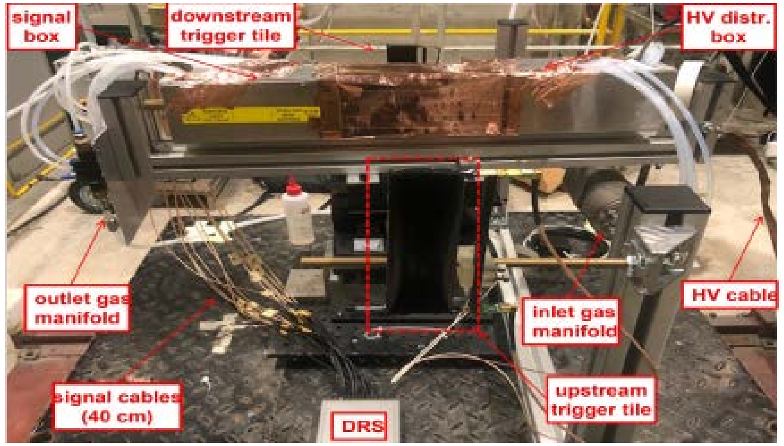
  - Aimed the maximum temperature of the readout module is below than 28 degrees.

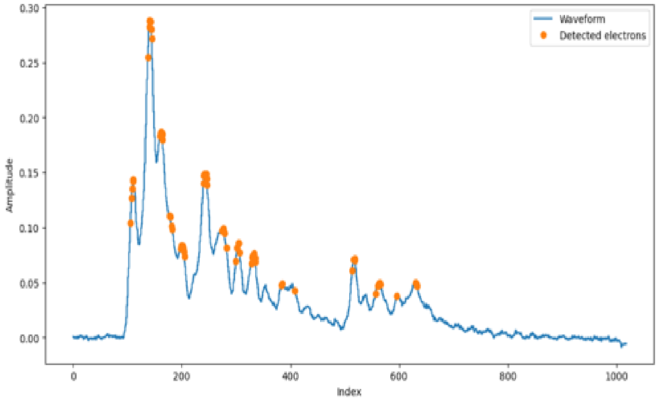
Taskforce and collaboration

- Active collaboration with LCTPC, ILD, CERN-DRD1 international groups. (DESY, Saclay, KEK, Bonn Uni.)
- Cooperation on: Data taking, key technology R&D of IBF and distortion

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





Research Team

- Core of the research team (**10 staffs + TPC group**)

  IHEP: **8 staffs + 4 students**

  Tsinghua: **2 staffs + 3 students**

- Collaboration of the research team (**6 staffs +10 students**)

  TPC: CIAE, Shandong University, Nankai University, Zhengzhou University and Liaoning University

  DC: INFN, 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 interr