Status of TPC R&D for CEPC

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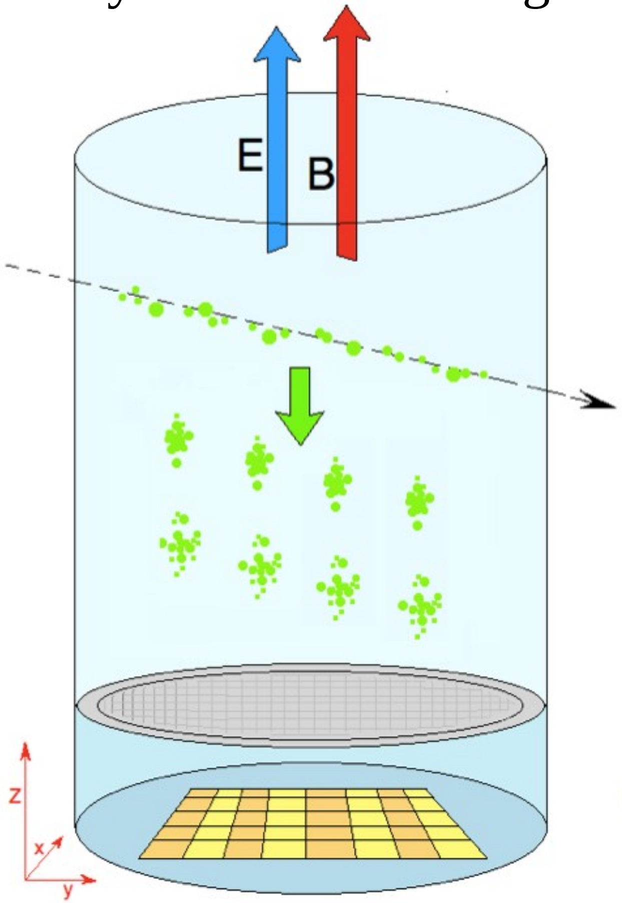
CEPC Track meeting, 2023.12.27

What is Time Projection Chamber?

- Operating principle: **Electric field and magnetic field are applied in parallel** in the TPC
  - 3-Dimensional (x, y, z) information
  - Momentum measurement, PID
  - Very low material budget



Principle of TPC detector

Momentum resolution

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\underbrace{\left(\frac{\alpha' \sigma_x}{BL^2}\right)^2 \left(\frac{720}{N+4}\right) p_\perp^2}_{\text{measurements}} + \underbrace{\left(\frac{\alpha' C}{BL}\right)^2 \frac{10}{7} \left(\frac{X}{X_0}\right)}_{\text{multiple scattering}}}$$

$p_\perp$: transverse momentum
σ_x : position resolution
B : strength of B-Field
N : # of measurement points
L : track detection length
$\frac{X}{X_0}$: radiation length of gas
α', C : constant

R.L. Gluckstern, NIM 24 (1963), 381

TPC only... $\frac{\sigma_{p_\perp}}{p_\perp} \approx 1 \times 10^{-4}\, p_\perp\, GeV/c$

Position resolution

$$\sigma_x = \sqrt{\sigma_0^2 + \frac{C_d^2 \cdot \boxed{z}}{N_{eff}}}$$

z: drift length
Neff: effective number of electron
Cd: diffusion constant of gas

depends on $\boxed{\text{drift length}}$

small position resolution σ_x

$$\sigma_x \approx 100\ \mu m$$

even at the large drift length of $2.2\ m$

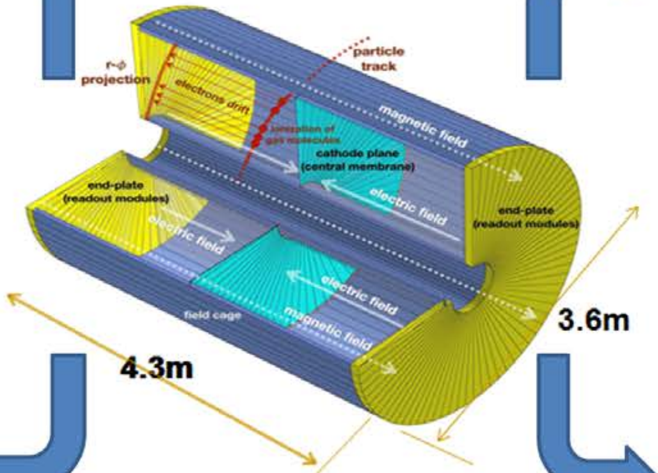
Motivation: TPC requiremetns from e+e- Higgs/EW/Top factories

- TPC can provide hundreds of hits with high spatial resolution compatible, with PFA design (**low X_0**)
  - $\sigma_{1/pt}$ ~10^{-4} $(GeV/c)^{-1}$ with TPC alone and σ_{point}<100μm in rϕ
- **Provide dE/dx and dN/dx with a resolution** <4%
  - Essential for Flavor physics @ Tera Z run

Pad readout TPC
- To meet Higgs physics
- 1mm×6mm of Pad
- TPC module
- TPC prototype with UV laser

TPC track detector for e+e- collider

Pixelated readout TPC
- To meet Z physics
- ~500μm of Pad
- TPC prototype with UV laser track
- dN/dx+dE/dx study



Ion back flow study
- Simulation of Ion Backflow
- Test the UV light created the ions by photoelectric effect
- Experimental study

PID performance Study
- Simulation of the ionization cluster in space
- PID studies of the different readout TPC prototype
- Experimental study

Key issues of TPC technology for e+e- collider

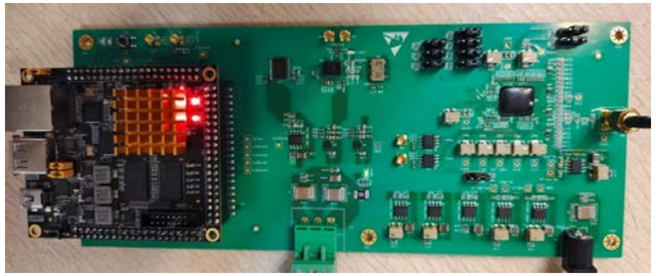
- Pad readout TPC for Higgs run at CEPC
  - TPC is **an irreplaceable tool for 3D track reconstruction and for particle identification with almost no material budget.**
  - **LP prototype have been validated** by the beam test @5GeV/e.
  - TPC is **essential for PID using dE/dx (<4%),** though a TOF with 10 ps or less resolution can help for moderate momenta(<20 GeV)
  - Central Tracking **is entrusted to a pad readout TPC detector**.

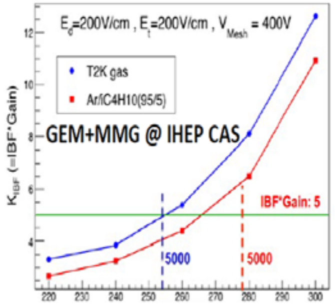
TPC parameters for Higgs run

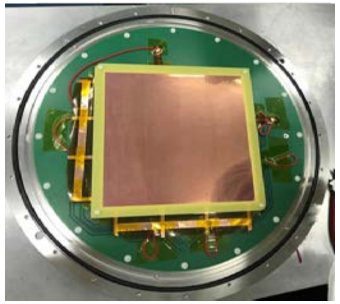
Parameters			
B-field	3.0T		
Geometrical parameters	r_{in}	r_{out}	z
	0.3m	1.8m	2.3m
Solid angle coverage	Up to cosθ ≃ 0.98 (10 pad rows)		
TPC material budget	≃ 0.05 X_0 including outer fieldcage in r		
	< 0.25 X_0 for readout endcaps in z		
Number of pads	≃ 10^6/1000 per endcap		
Pad pitch/ NO. of Padrows layers	≃ 1 × 6 mm^2 / 220 points per track in rφ		
σ_{point} in rφ	≃ 60 μm for zero drift, ≤ 100 μm overall		
σ_{point} in rz	≃ 0.4 – 1.4 mm (for zero – full drift)		
2-hit separation in rφ	≃ 2 mm		
dE/dx resolution	≤ 4 %		
Momentum resolution at B = 3.0 T	$\delta(1/p_t) \simeq 1 \times 10^{-4}$/GeV/c (TPC only)		

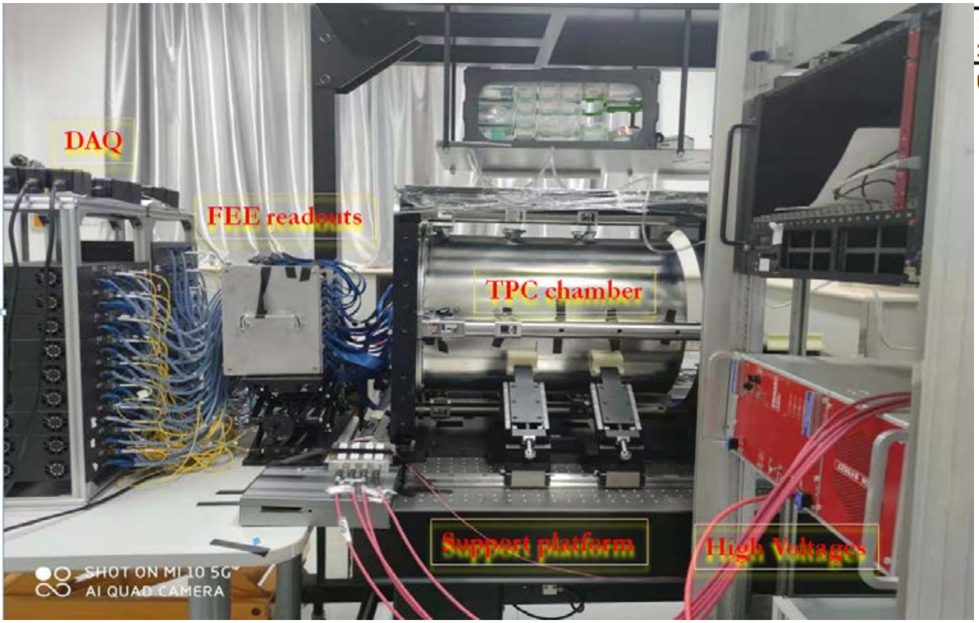
Pad readout TPC – Low power consumption and hybrid readout @IHEP

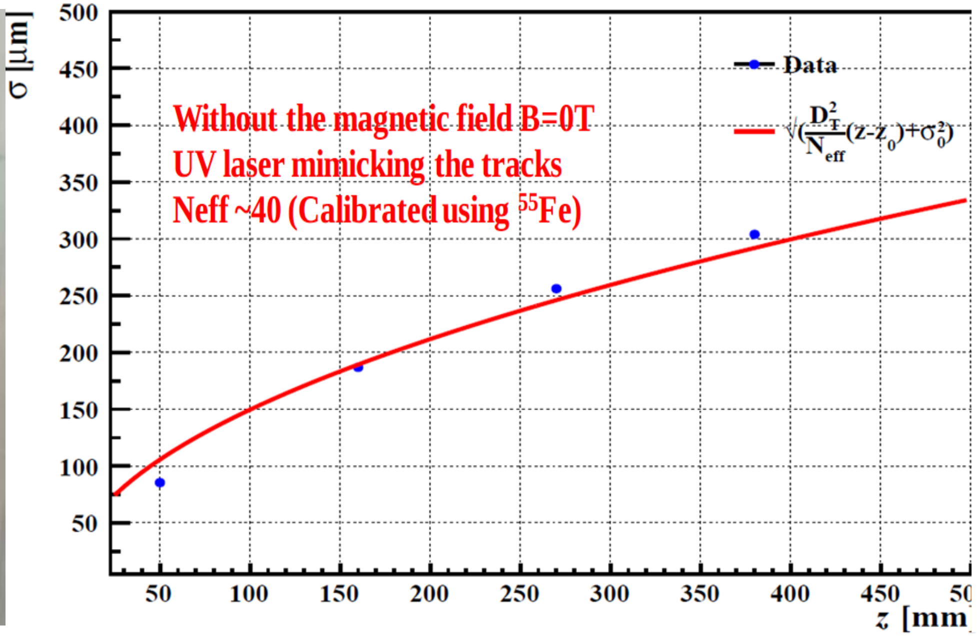
- **Low power consumption ASIC has been developed for TPC readout.**
  - Low power consumption FEE ASIC (**~2.4 mW/ch** including ADC)
- **Hybrid readout module has been developed:**
  - IBF×Gain **~1 at Gain=2000** validation with GEM/MM readout
  - Spatial resolution of **$\sigma_{r\varphi} \leq 100\ \mu m$** by TPC prototype
  - Pseudo-tracks with 220 layers (**same as the actual size of CEPC baseline detector concept**) and dE/dx is about 3.4 ± 0.3%

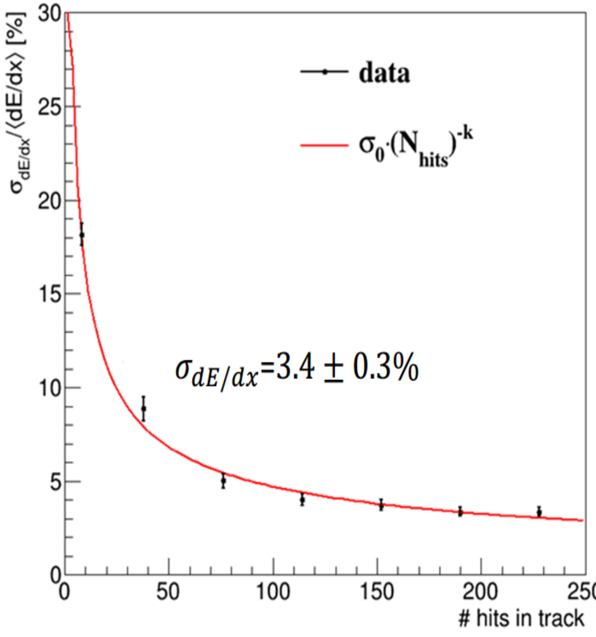








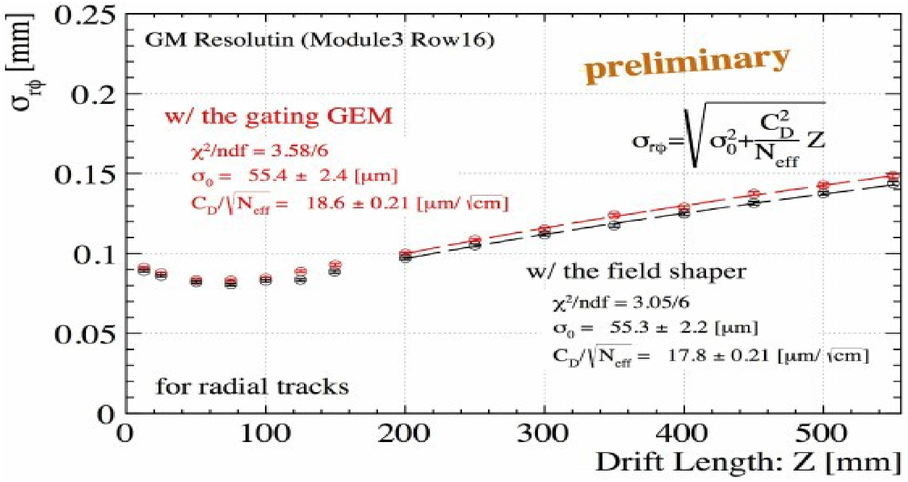


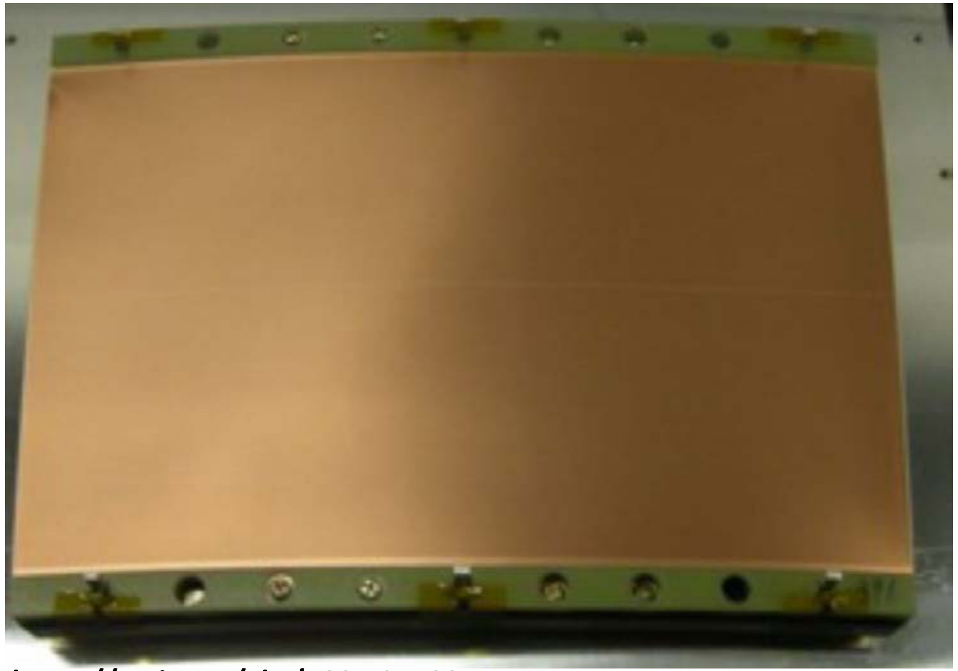


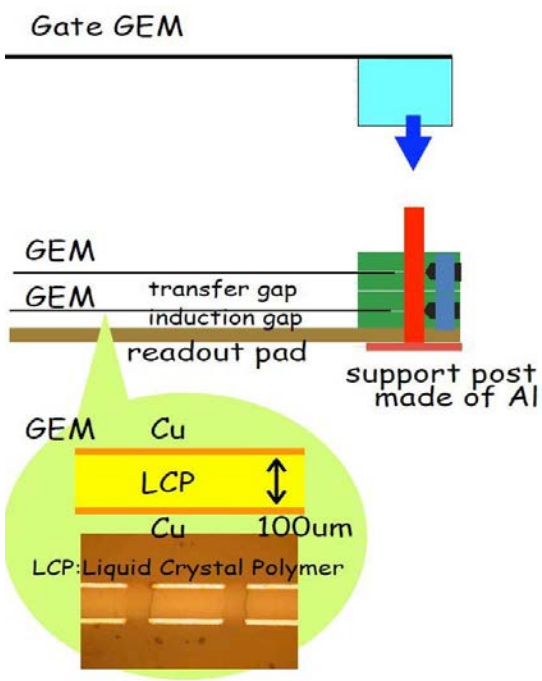
https://doi.org/10.1016/j.nima.2022.167241

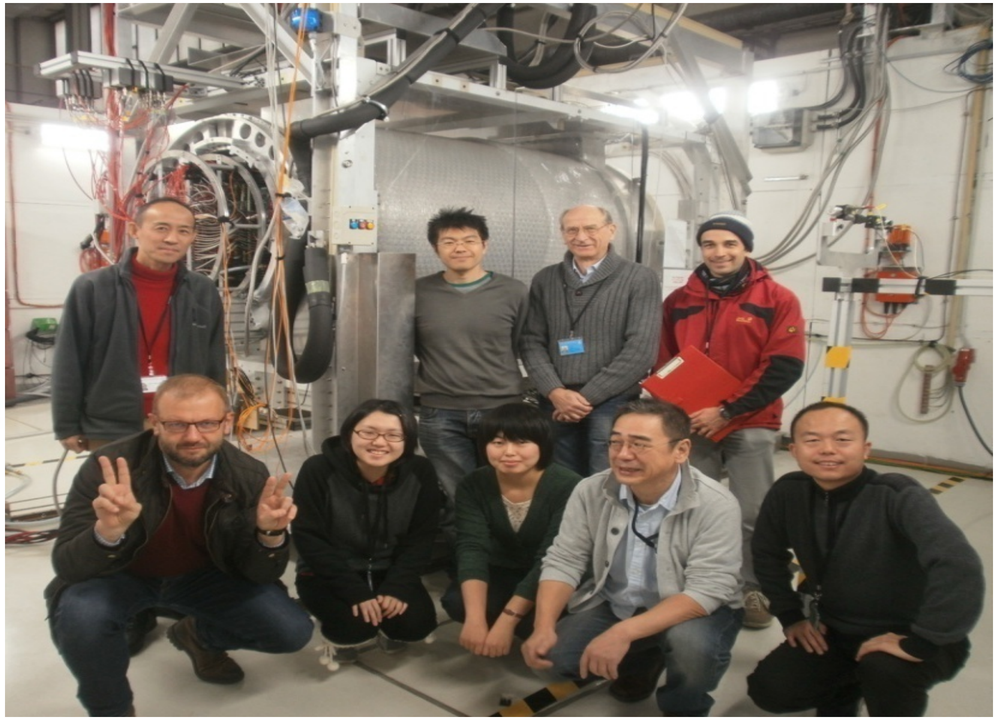
Pad readout TPC technology – GEMs readout @LCTPC

- **TPC prototype have been studied the beam under 1.0T.**
  - GEMs with 100μm LCP insulator
  - Standard GEM from CERN
- Design idea of the GEM Module:
  - **No frame** at modules both sides
  - Spatial resolution of $\sigma_{r\phi} \leq 100$ μm, more stability by the broader arcs at top and bottom





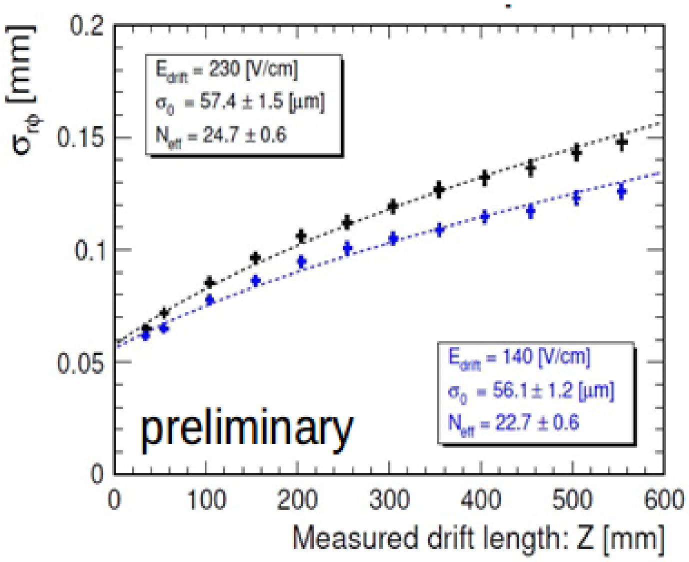


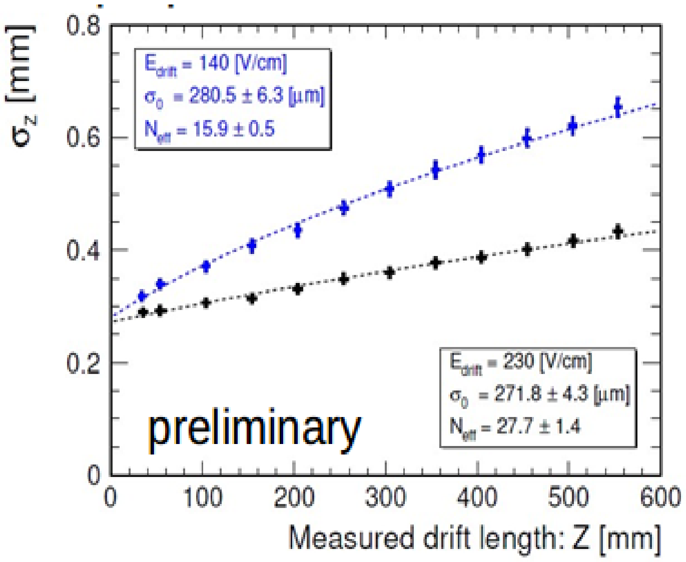


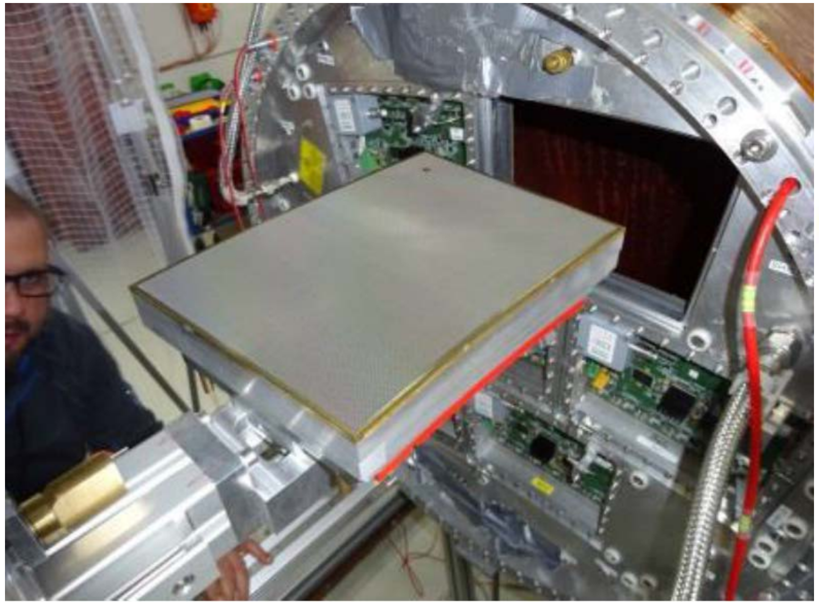
https://arxiv.org/abs/1801.04499

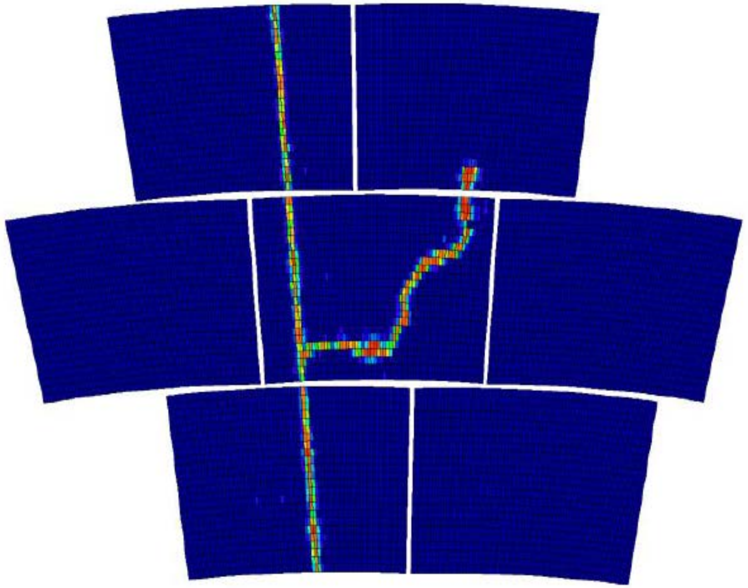
Pad readout TPC technology – Resistive Micromegas readout @LCTPC

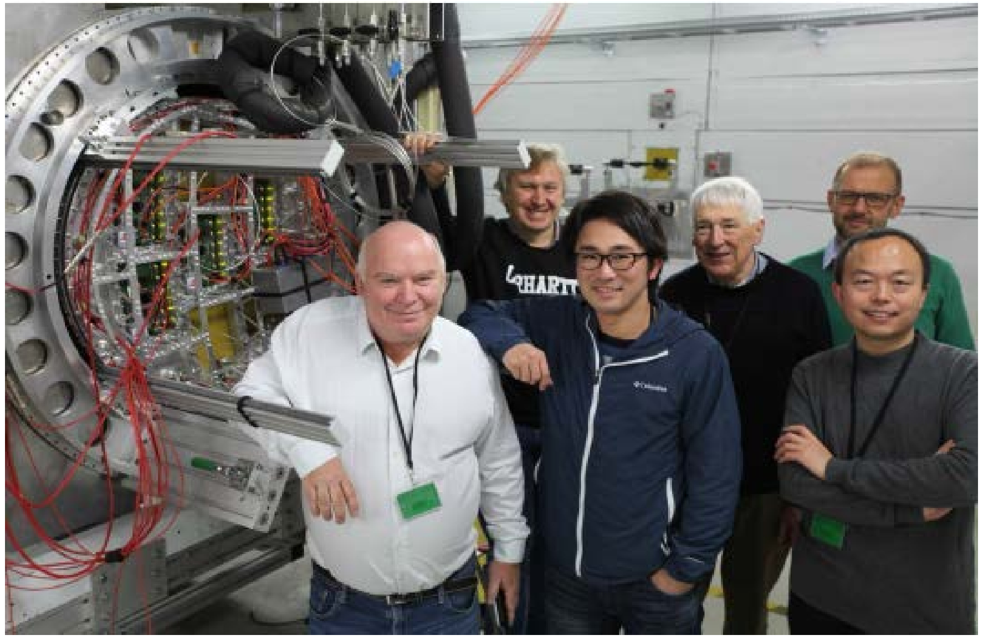
- **Resistive Micromegas has been studied by the beam under 1.0T.**
  - Bulk-Micromegas with 128 μm gap size between mesh and resistive layer.
- HV scheme of the module (ERAM) places grid on ground potential
  - Spatial resolution of $\sigma_{r\phi} \leq 100$ μm







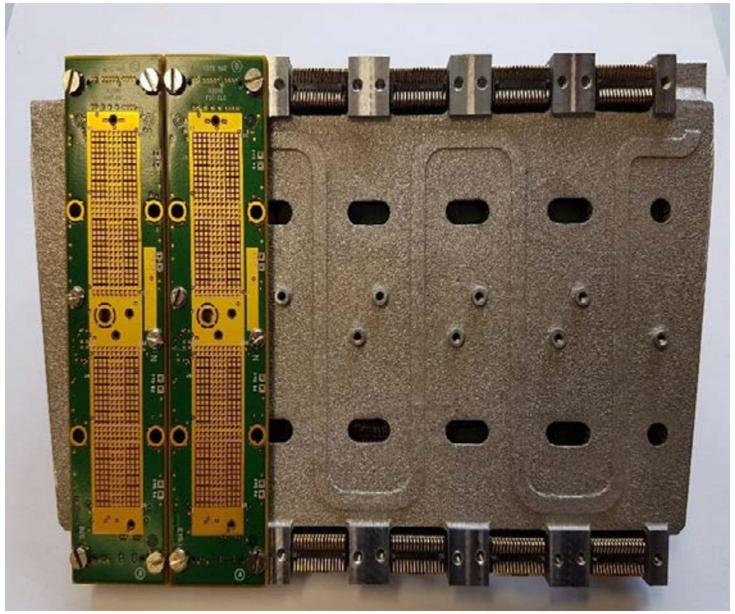


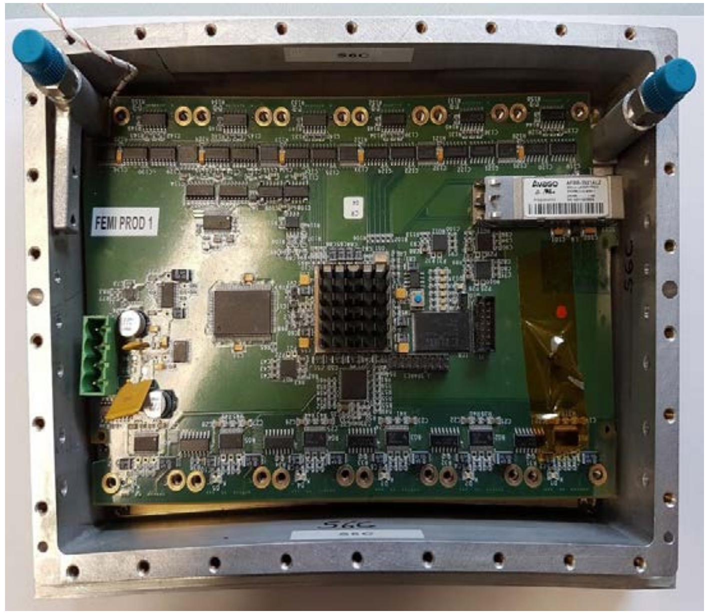


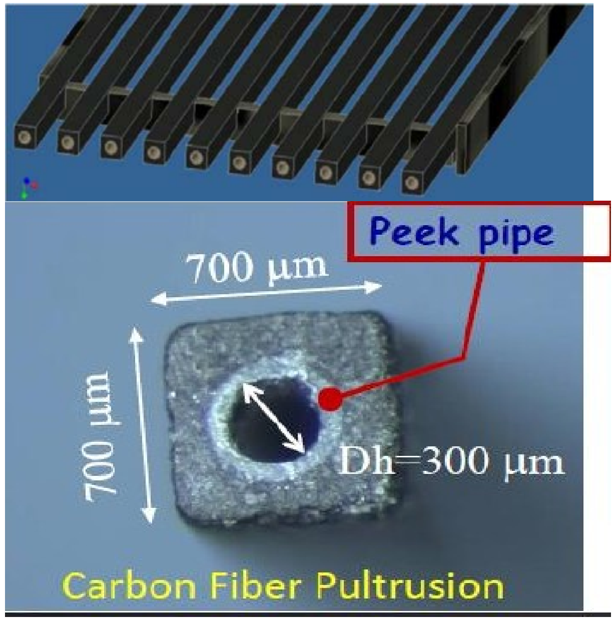
https://doi.org/10.1016/j.nima.2019.162798

Cooling system for readout electronics

- 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 is **validated at LCTPC**.







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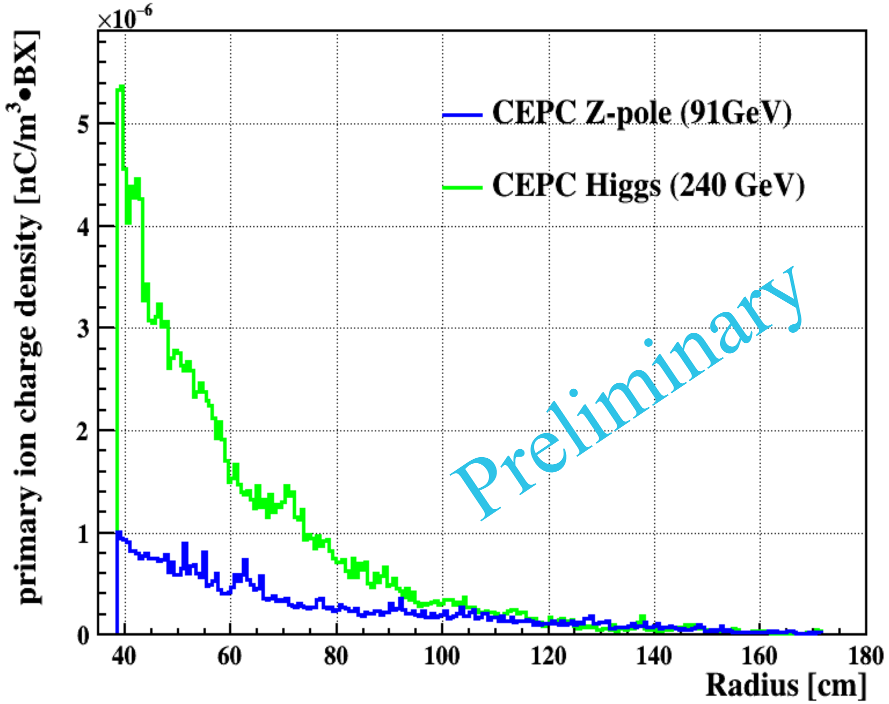
- Pixelated readout TPC for Z pole run at CEPC
  - In the Tera Z conditions, **these are typically of several hundred microns per point to a mm**, and even centimeters if one consider the charge created by the machine background.
  - In the Tera Z conditions at a high-luminosity circular collider, the **secondary ions back-flowing need to be strongly suppressed**, and corrections have to be dynamically applied using the pixelated readout.
  - Some **intense R&D program has to be addressed** even than simulation.

Results of the estimation ion charge density in Chamber

- **For Higgs run, no problem detector factor for TPC**
- **For Z pole run**
  - **TPC with IBF*Gain=1 at CEPC-91**

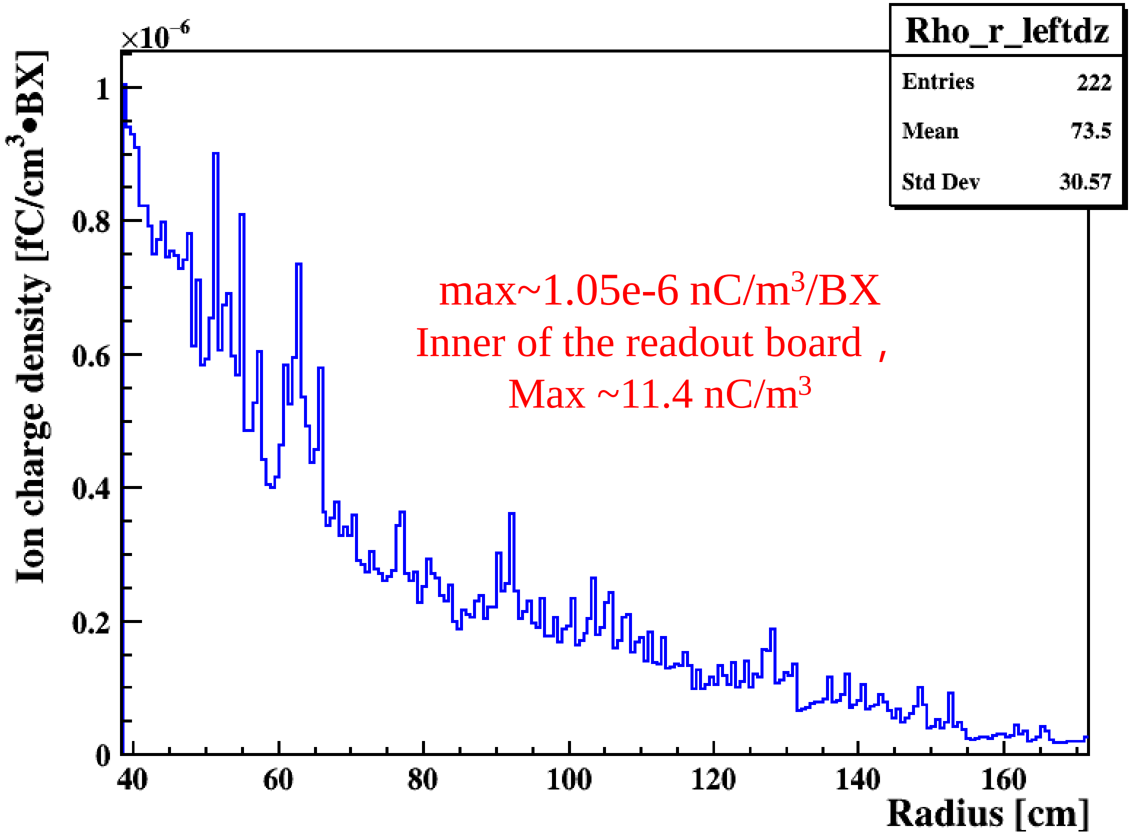
    → at best, less or similar space-charge as at ALICE



Collider Detector Model	CEPC_v4	CEPC_v4
Beamstrahlung pairs	CEPC Z-pole(91GeV)	CEPC Higgs(240GeV)
BX freq.	1/23 ns	1/680 ns
primary ions/BX	27.37 k	72.36 k
primary ions at any time	5.95×10^{11}	5.32×10^{10}
average primary ρ_{ion} [nC/m^3]	2.43	0.22
max (single BX) [nC/m^3/BX]	1.05×10^{-6}	5.4×10^{-6}
max (steady state) [nC/m^3]	11.4	1.98

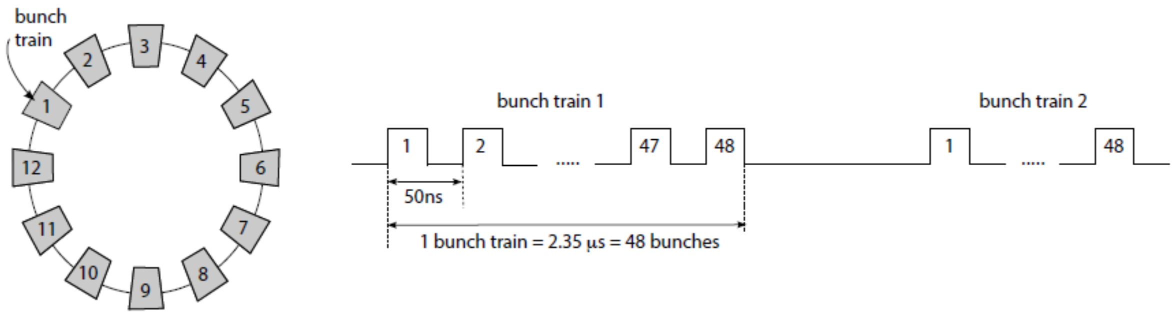
Compare to ALICE-TPC environment

- Calculation of TPC radial ion space charge density: z=-200cm， (dz=10cm，dr=6mm)
  - $d\Omega = 2\pi r\, dr\, dz$; $\rho_{ion} = \frac{n_{ion}}{d\Omega}$
- Each BX~ **1.05e-6 nC/m³/BX**，0.2e-6 nC/m³/BX (compared to uniformly distributed)
- Stable Max~ 1.05e-6 nC/m³/BX × 1/23ns × 50% × η = 11.4 nC/m³ (Only primary ions, η ionization efficiency)



ALICE TPC upgrade TDR: CERN-LHCC-2013-020

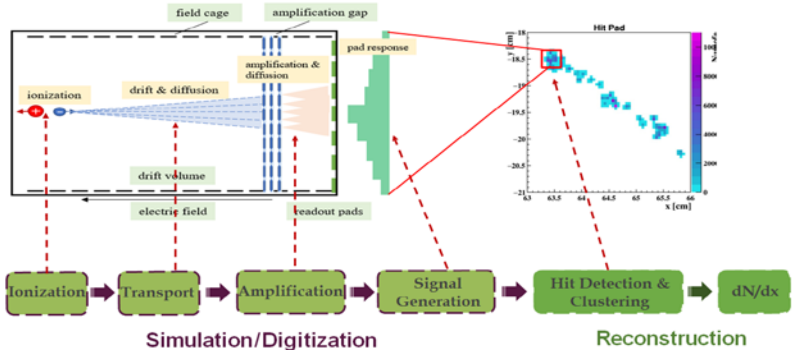
	max (single BX)	BX freq	max (steady state)
ALICE		50k	120 nC/m³ with IBF=20

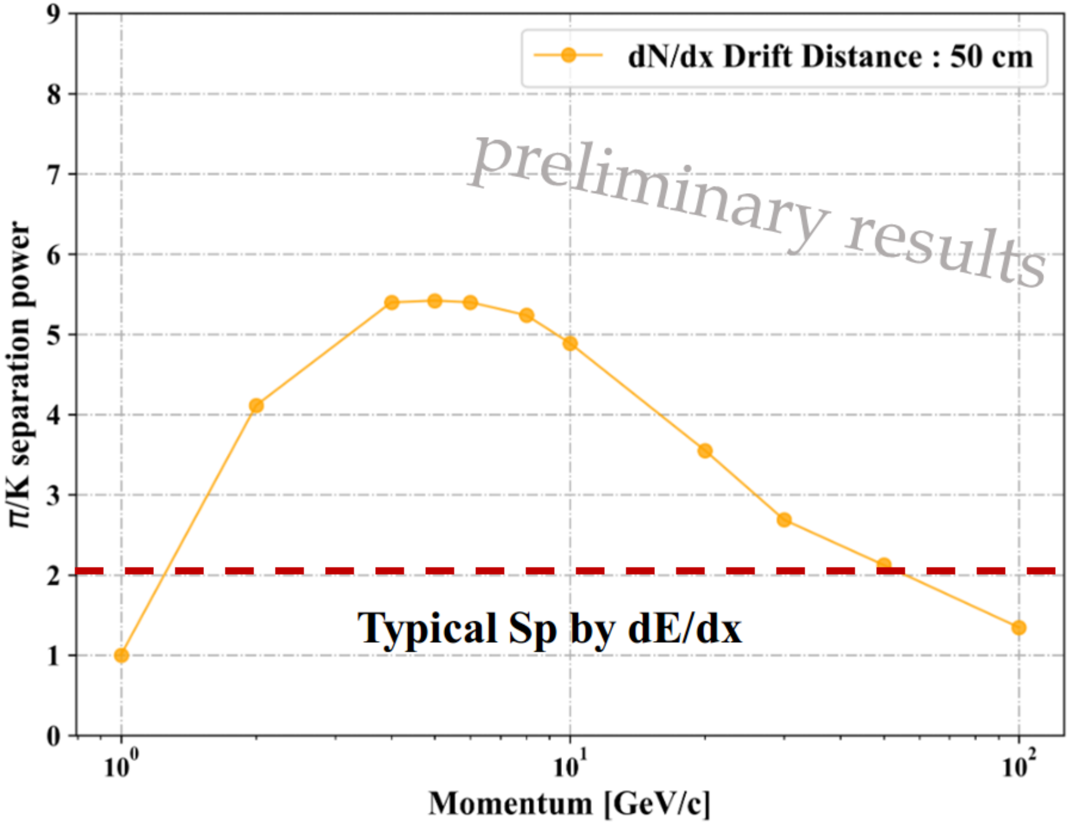


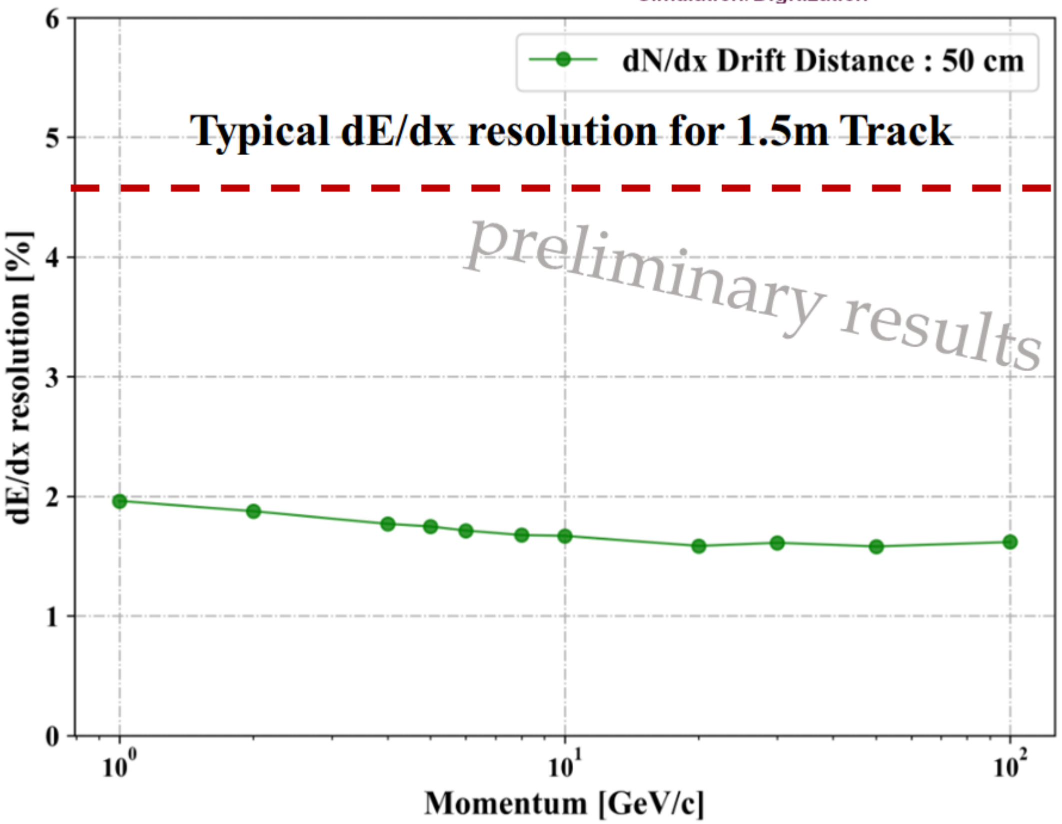
Simulation of the pixelated TPC - ongoing

- Separation power was obtained based on the current reconstruction algorithm as well as the results of the resolutionSetup the optimaztion simulation framework.
- π/K resolution **is better than 3σ at 20 GeV and 50 cm drift distance**.
- The dN/dx has an **good potential** to improve the resolution.

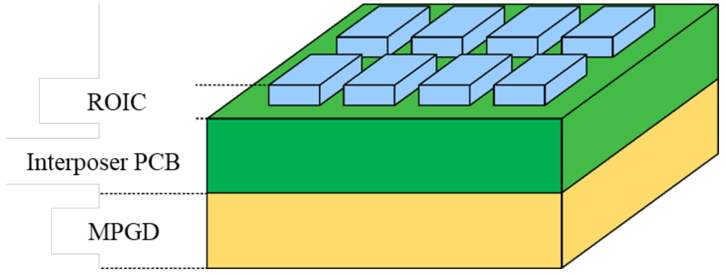
- TPC detecror module simulated **under 2T and T2K gas.**

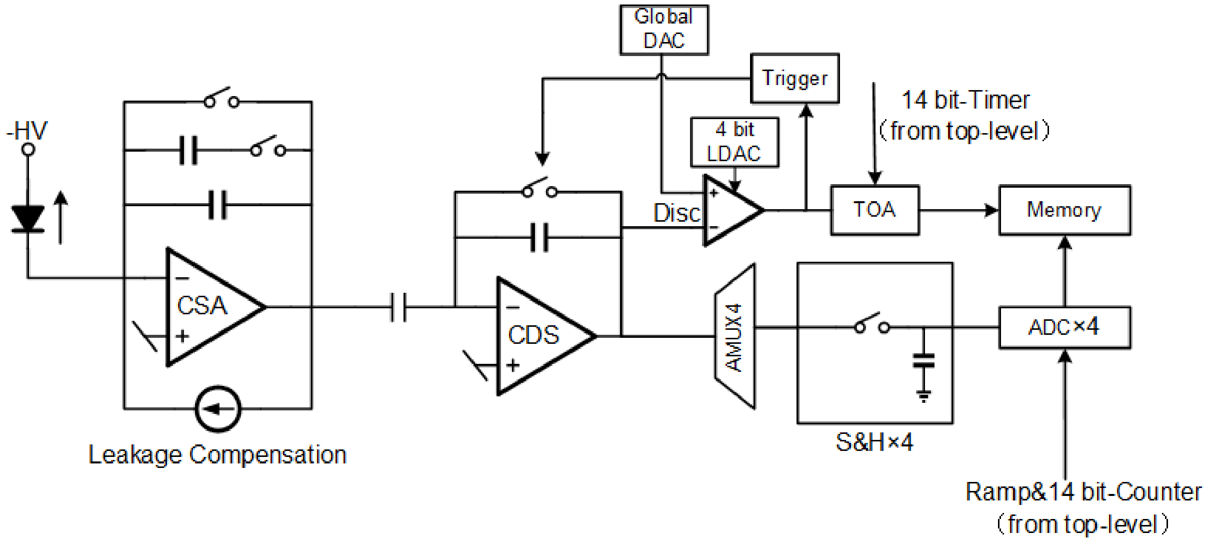


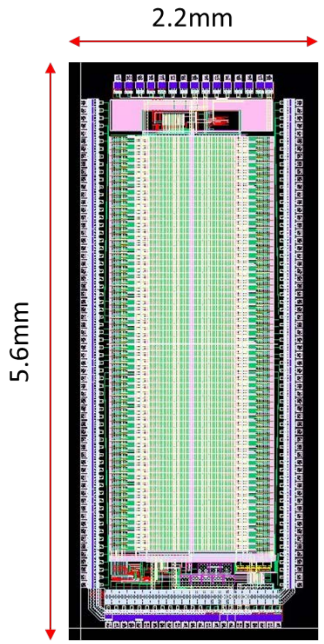




- **Pixel readout R&D started and the design and testing of two versions of the chip completed.**
- ROIC +Interposer PCB as RDL
    - High metal coverage, 4-side buttable
    - Low power Energy/Timing measurement ASIC
    - **~100 e noise**
    - 5 ns drift time resolution
    - **<100 mW/cm2**
- 2nd version chip arrived and the tests are onging.



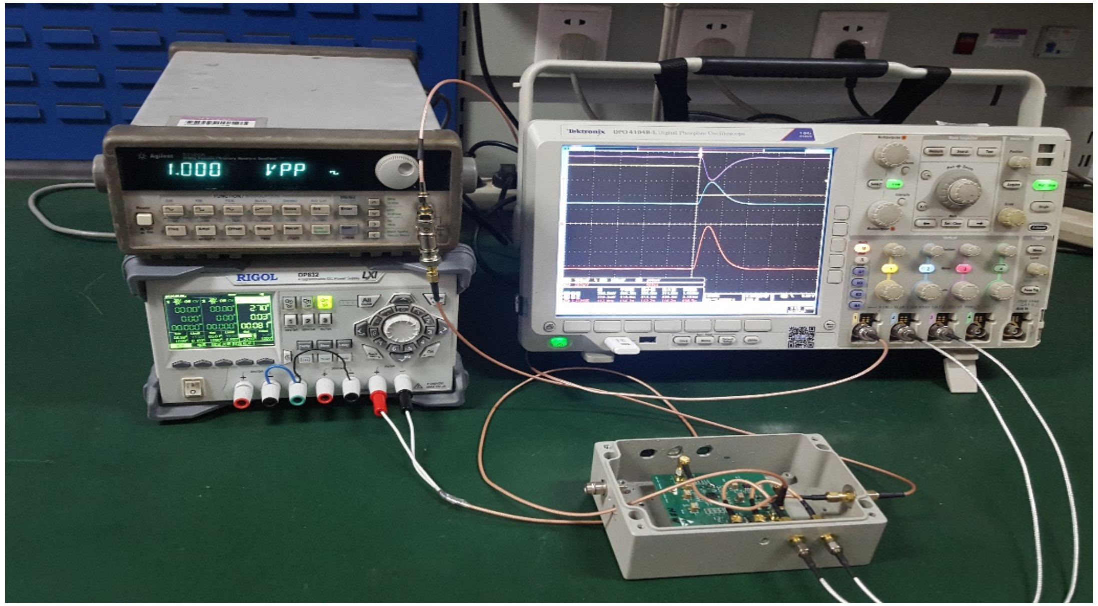


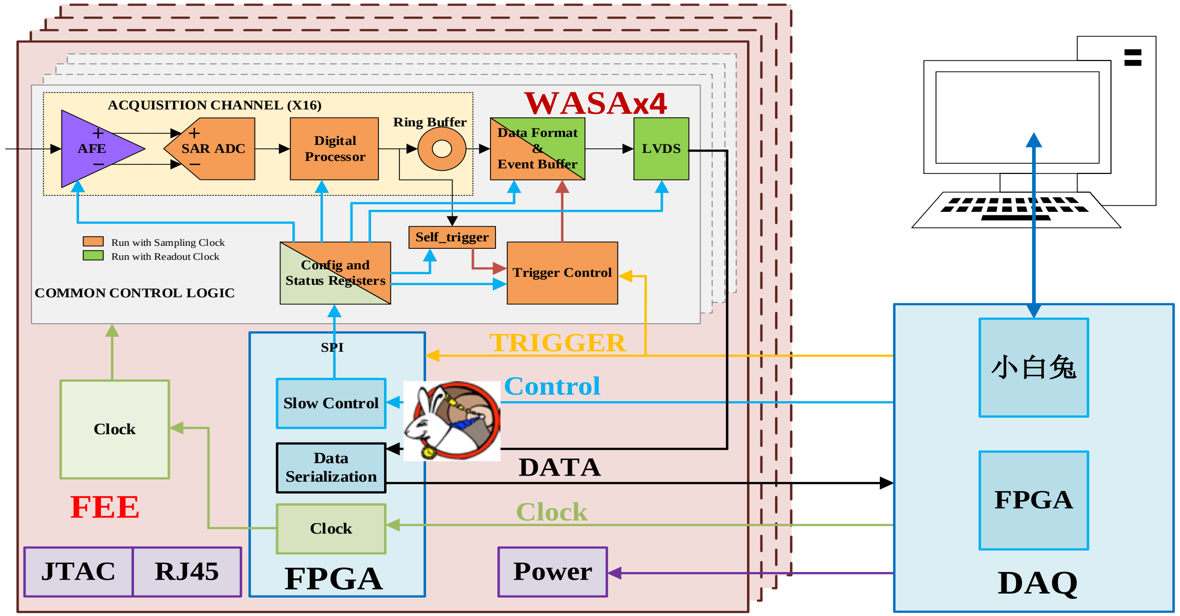


TPC R&D toward CEPC Phy.&Det. TDR

- Simulation and experiments studies needed for **CEPC TDR**.
  - MDI region optimized, lower Gain×IBF and reach the same level primary ions(Gain: 2000, IBF: ~0.1%)
  - TPC with IBF at Tera-Z with **quasi continuous collisions** @ CEPC/FCCee
    - Apply Micromegas+GEM , mutil-mesh Micromegas
    - Nano-material through which ions can be controlled
      - Ion backflow R&D with the **Grapheme foil** → Collaboration: CEA-Saclay, Shandong University

- Low **power consumption** readout R&D of TPC FEE board based on WASA.
- Tests Low power Energy/Timing chip of the pixel readout chip. → Collaboration: Tsinghua University





Summary and Conclusion

- **In CEPC TPC study group, TPC detector prototype R&D using the pad readout towards the pixelated readout for the future e+e- colliders.**

- **TPC as the main tracker detector to satisfy the physics requirements :**
  - **For Higgs run,** W and top running, **no problem** for all TPC readout technologies.
    - Central Tracking **is entrusted to a pad readout TPC detector**.
  - **For high luminosity (2×10^{36}) Z pole run**:
    - Pixelated readout TPC is a good option at **high luminosity** on the circular e+e- collider.
    - The gating will not be possible, so we need an ion back flow suppression without gating R&D (double or triple mesh/mutil-Mesh, graphene membrane...)
    - Some **intense R&D program has to be addressed**.

Many thanks!