Update MDI study of TPC Technology @ Tera-Z on CEPC

Huirong Qi
Institute of High Energy Physics, CAS

March 29, 2023, Hengyang

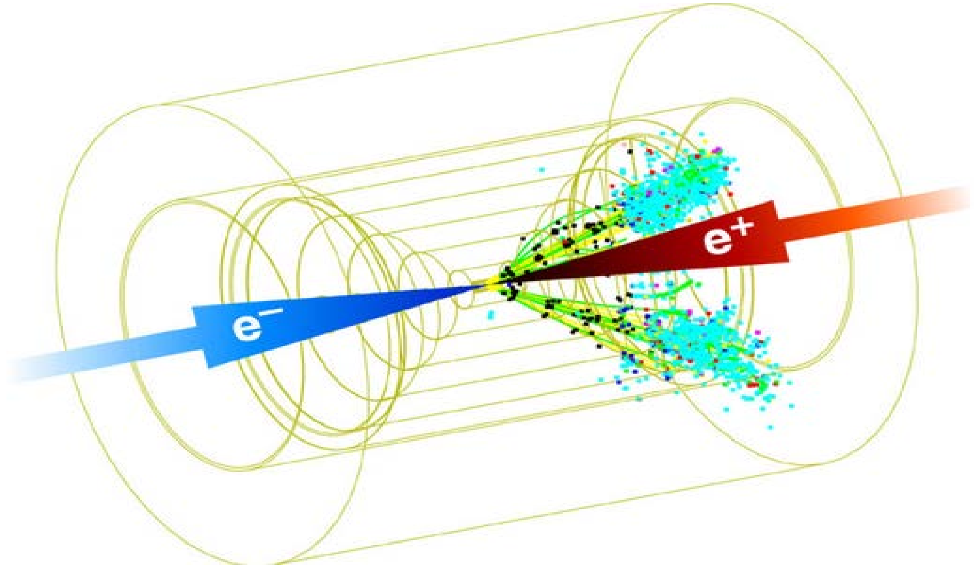
Content

- **Motivation of TPC for e+e- colliders**
- **MDI study of TPC technology**
- **Toward pixelated readout**
- **Summary**

e^+e^- colliders: Sources of Detector Backgrounds

- Beam-beam interactions (disrupted **primary beam, beamstrahlung photons, e+e- and mu+mu- pairs and hadrons** from beamstrahlung and gg interactions, and extraction line losses) and radiative Bhabhas
  - $e^+e^- \longrightarrow e^+e^-\gamma$ electron-positron scattering

- From the standpoint of integrated background, e+e- circular collider is relatively '**very clean**' machines. Average integrated hadronic fluxes produced at the IP are about several orders of magnitude lower compared to LHC. However, the Tera-Z are not so drastically different.

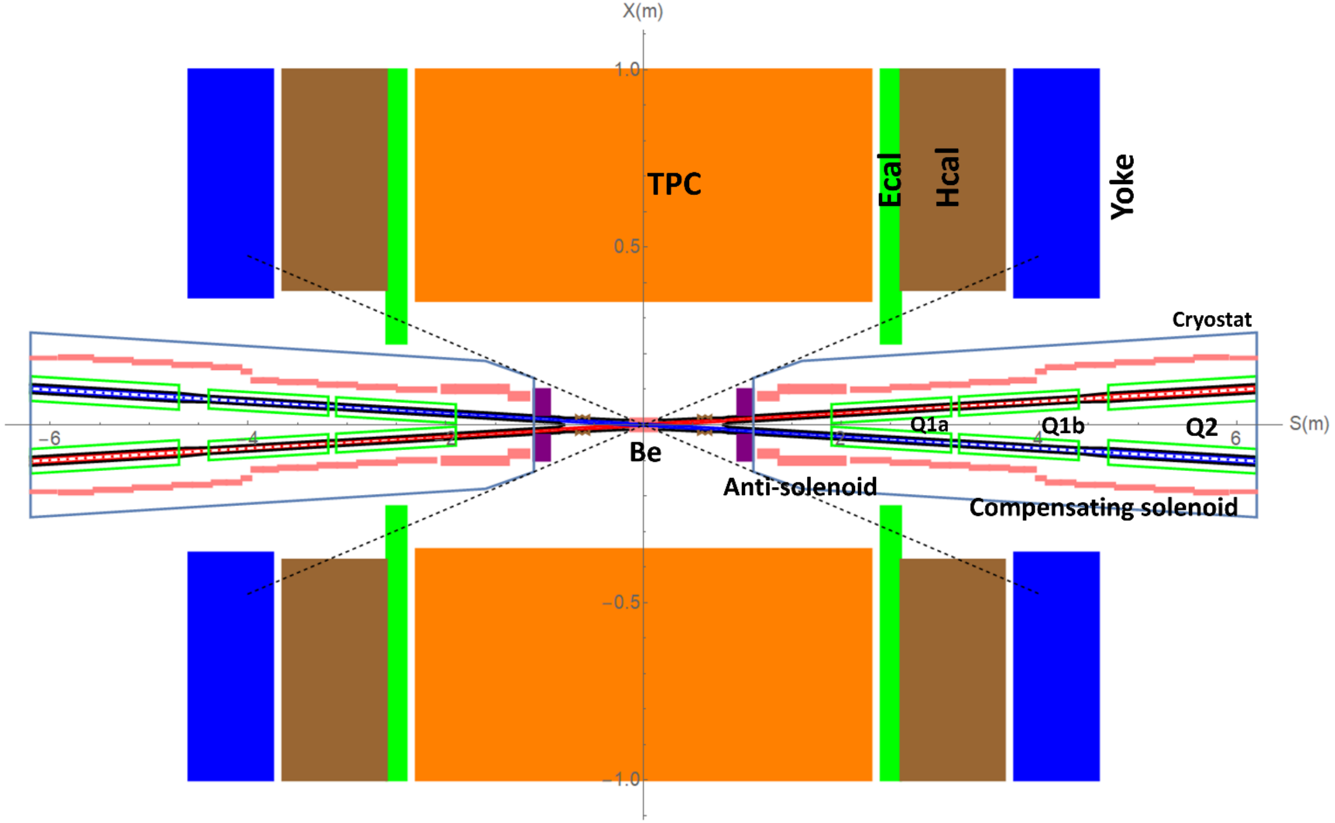


MDI region

e^+e^- colliders: Sources of Detector Backgrounds

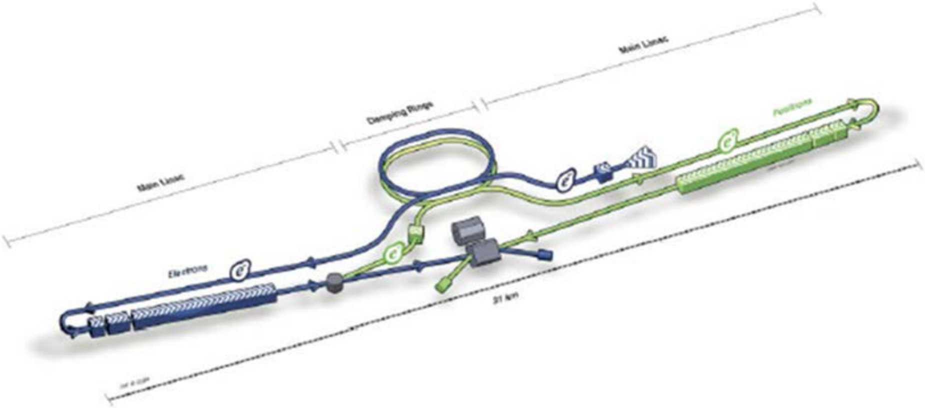
- In general, this source is well understood and under control: it scales with luminosity, one should transport interaction products away from IP and **shield/mask** sensitive detectors, and exploit detector timing
  - Fox example: Make limiting apertures (collimators or shield) as far from IP as possible. Suppress muon flux far from IP by thick magnetic walls.

3.0T for Higgs
High luminosity (10^{36})
2.0T for Z
Beam crossing angle of 33mrad

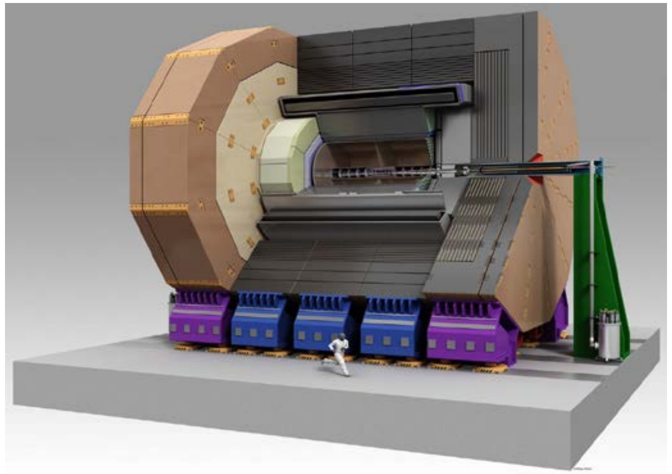


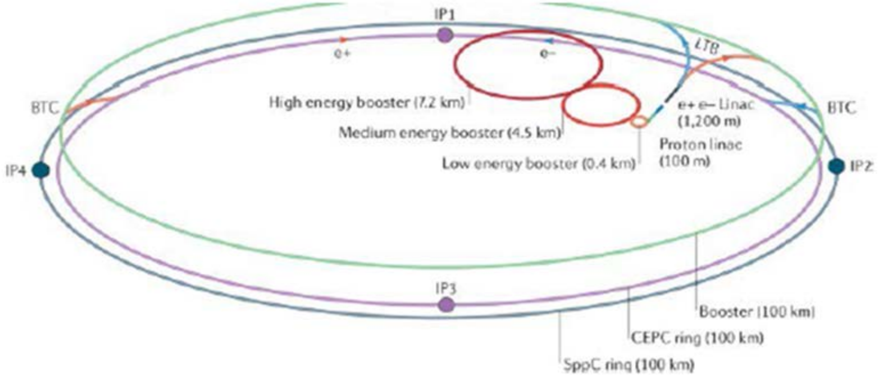
TPC technology for the future e+e- colliders

- A TPC is the main tracking detector for **some candidate experiments at future e+e- colliders**
    - ILD at ILC and the baseline detector concept of CEPC
- TPC technology can be of interest for other future colliders (FCC-ee, EIC, KEKb…)

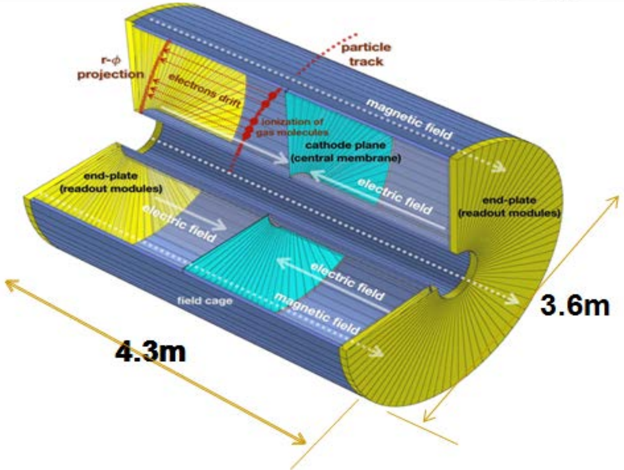


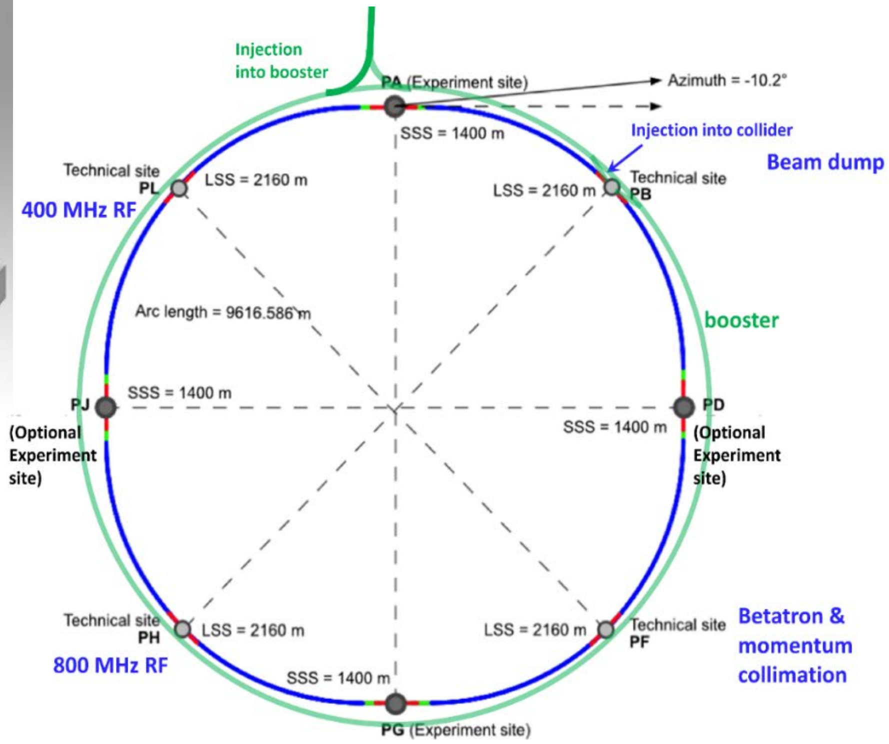
International Linear Collider (ILC)





Circular Electron Positron Collider (CEPC)



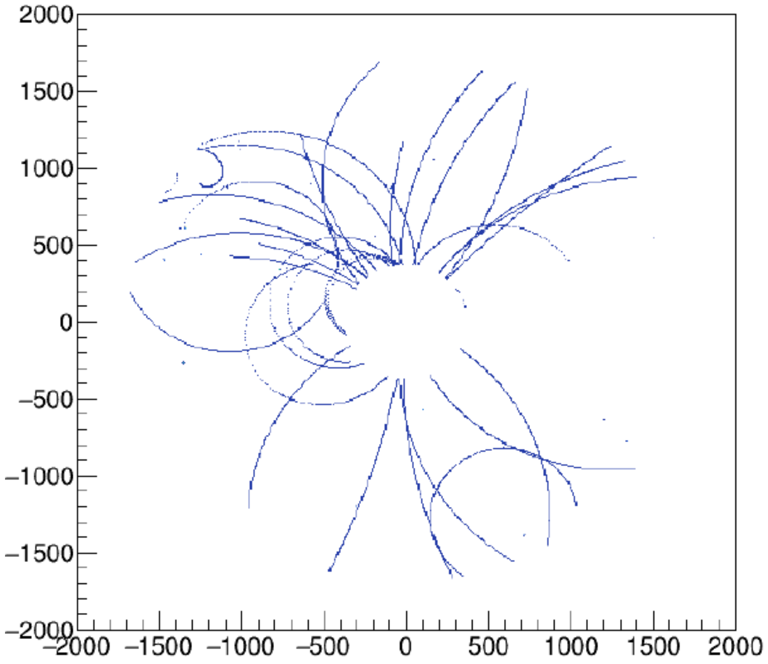


Future Circular Collider (FCC-ee)

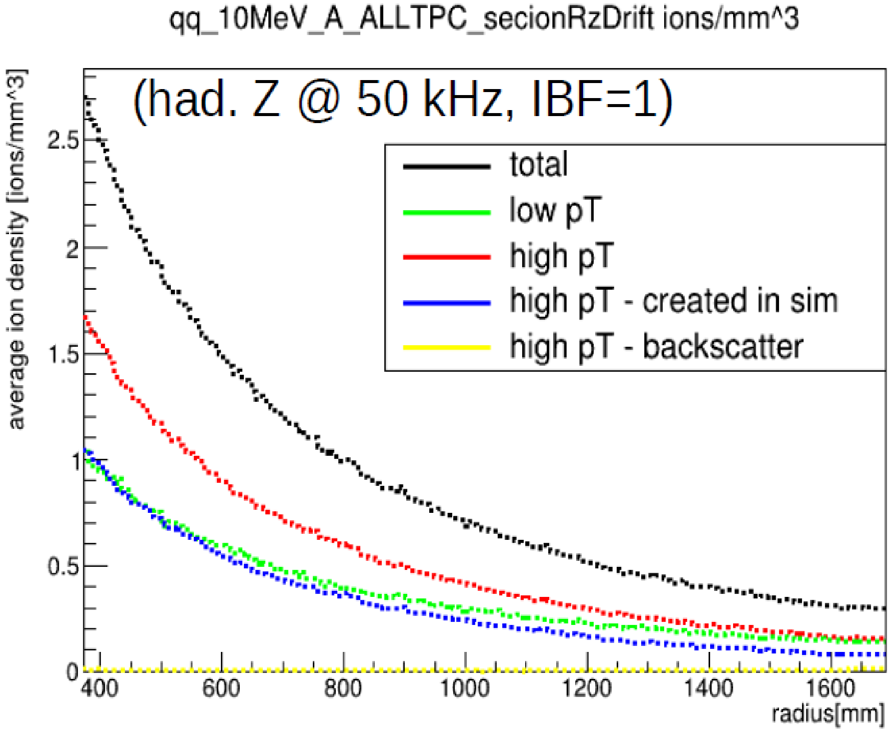
https://arxiv.org/abs/2203.06520

Ions in TPC chamber at Tera-Z

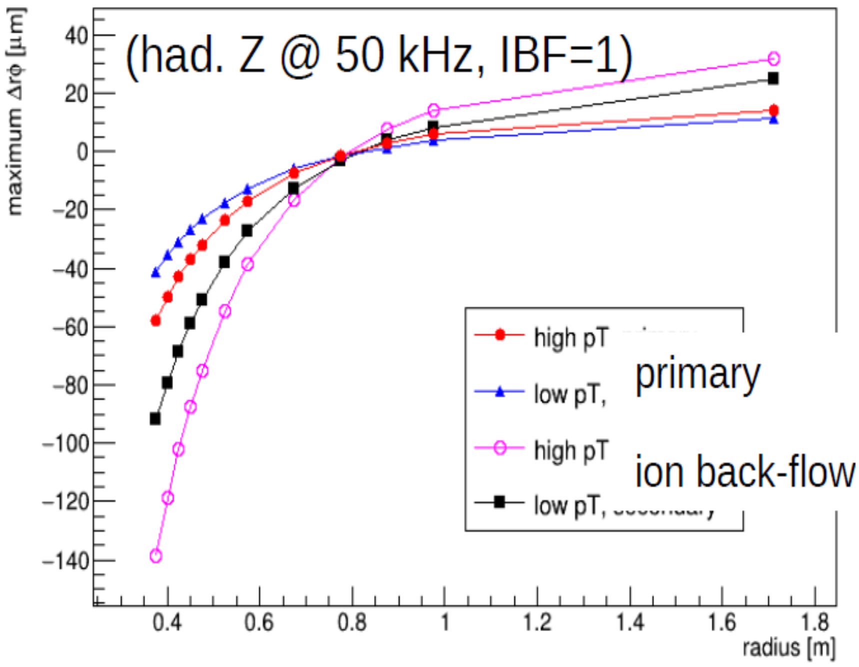
- Ions accumulate in TPC volume(**High luminosity at Z pole: 10^{36}**)
  - Primary ionization
  - Ion Back-Flow from amplification (“IBF”, dominant effect)
  - TPC ion density and resulting distortions due to **hadronic Z decays**
  - Ions from ~20k hadronic Zs are present in the TPC at any time



Hits in X-Y plane of TPC @qq



Average radial distribution of back-flow ion density



Max distortion in r-φ direction

Need investigation of the electrons/ions density

- Simulation results based on CEPC's parameters (**High luminosity at Z pole**)
- CEPC or others detector will meet the **massive electrons/ions in the detector chamber**
- To investigate and create the stable electrons/ions in the specific area to study the deviation
- Positive ion feedback in Z physics **(gain ~2000, IBF ratio ~0.1%)**

Electric field analysis

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon} \longrightarrow$$

Cylindrical coordinates

$$\phi(r,\theta,z) = \sum_{m=-\infty,\infty} \phi_m(r,z)e^{im\theta},$$

$$\phi_m(r,z) = \int_{-\infty}^{\infty} \Phi_m(r,k)e^{ikz}dk,$$

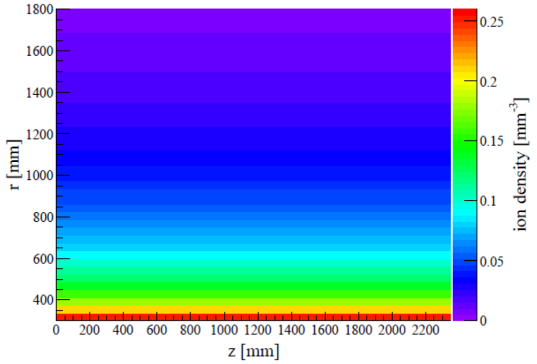
$$\Phi_m(r,k) = K_m(kr)\int_0^r R_m(r',k)\, I_m(kr')\, r'\, dr' + I_m(kr)\int_r^{\infty} R_m(r',k)\, K_m(kr')\, r'\, dr'$$

$$R_m(r',k) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \rho_m(r',z')\, e^{-ikz'}\, dz'$$

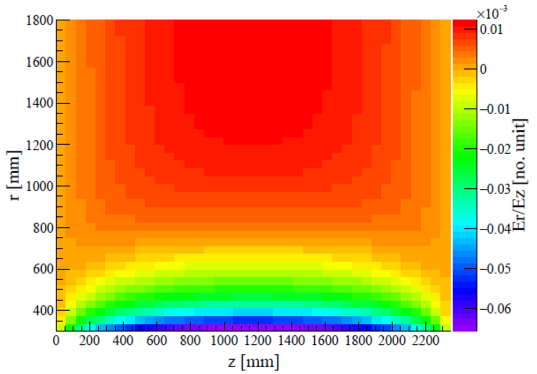
$$\rho_m(r',z') = \frac{1}{2\pi}\oint \frac{\rho(r',\theta',z')}{\epsilon_0} e^{-im\theta}\, d\theta'$$

Resnati F. Modelling of dynamic and transient behaviours of gaseous detectors[J]. 2017.

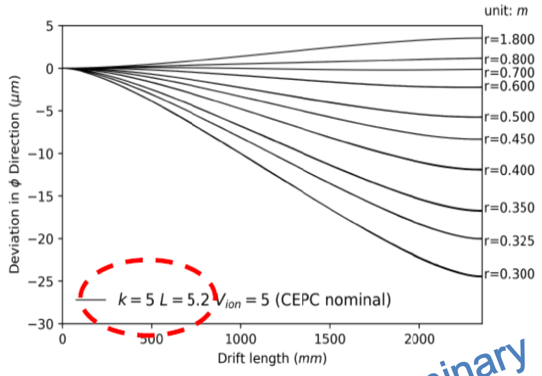
Ions density in chamber



E_r/E_z

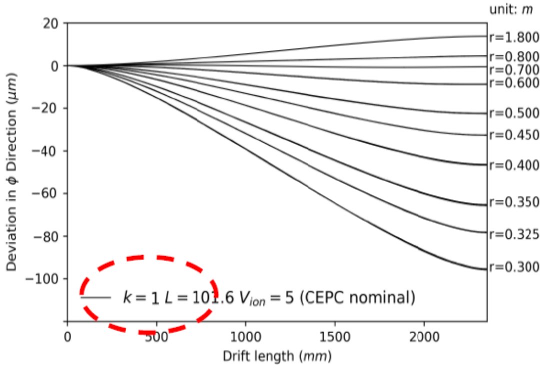


Higgs



Z

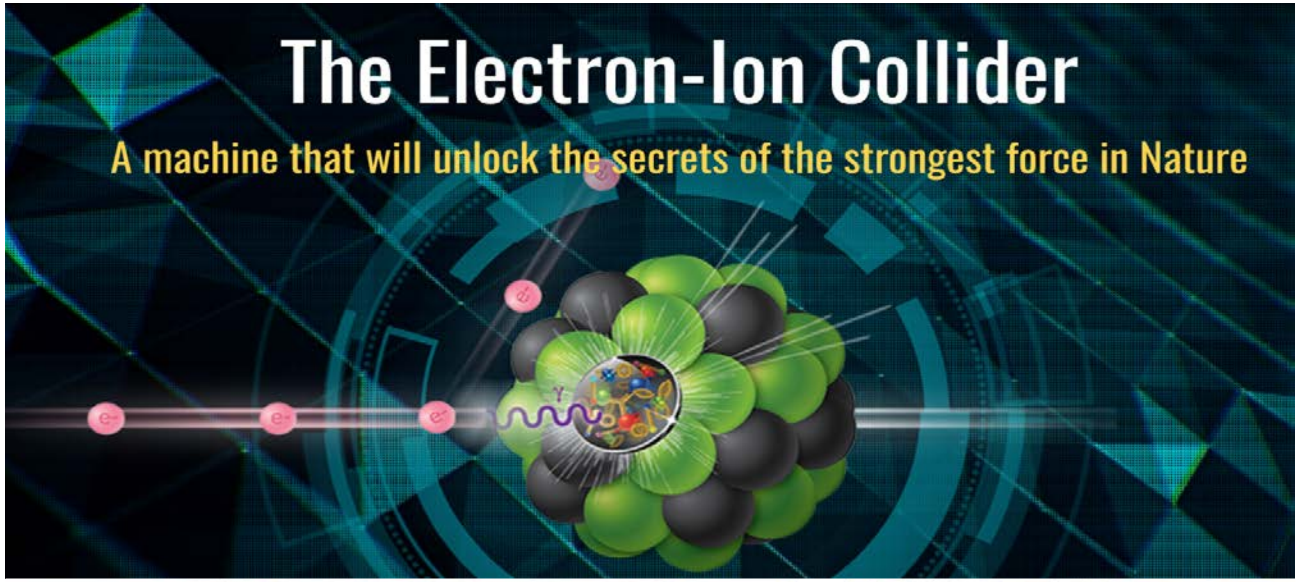
Preliminary

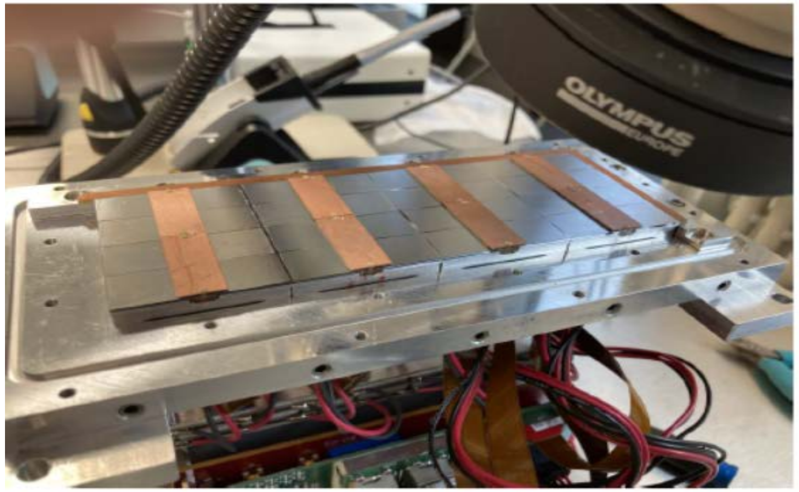


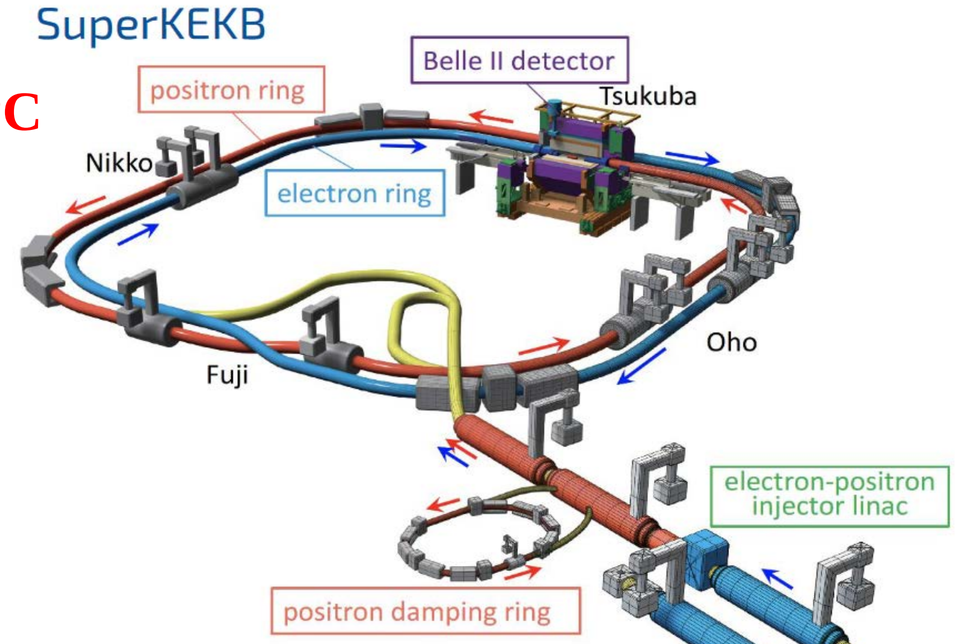
- MDI study of TPC technology
  - Ions produced by machine-related backgrounds
  - Some references of high luminosity e+e- collider

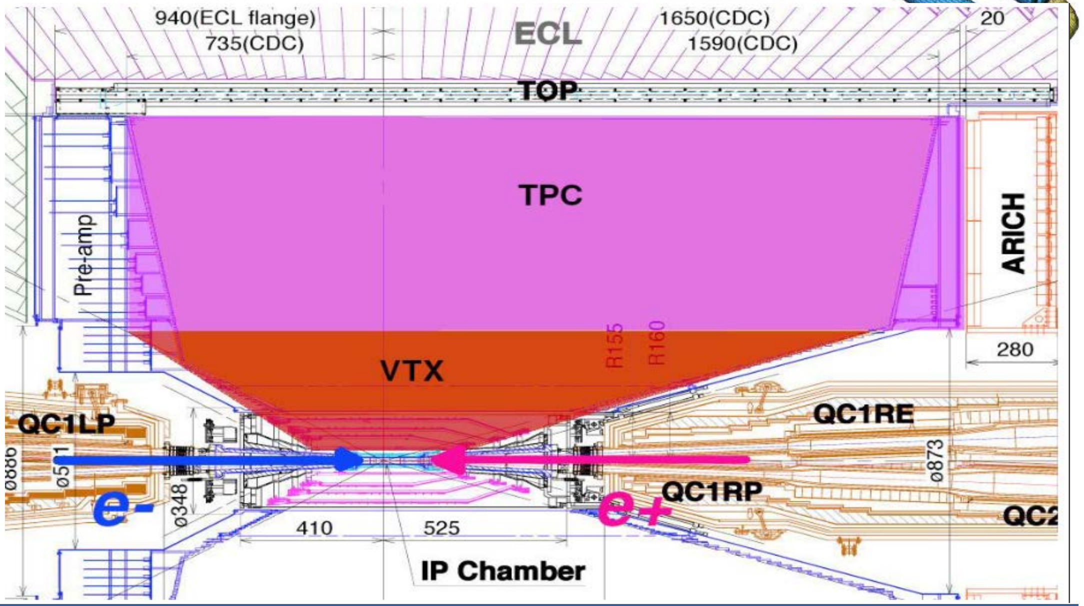
Upgrade Proposal: TPC for EIC and BELLEII

- EIC: mini-TPC project from Bonning University
- BELLEII: Proposal to replace the drift chamber with a **tracking TPC**



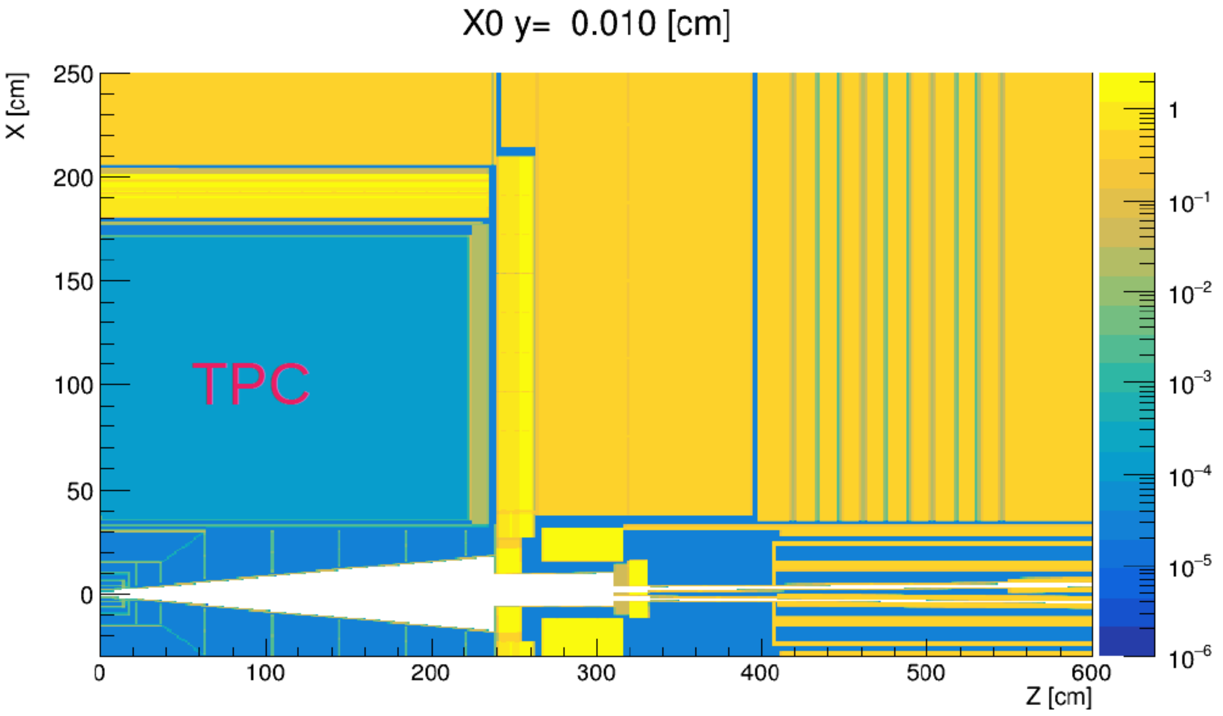




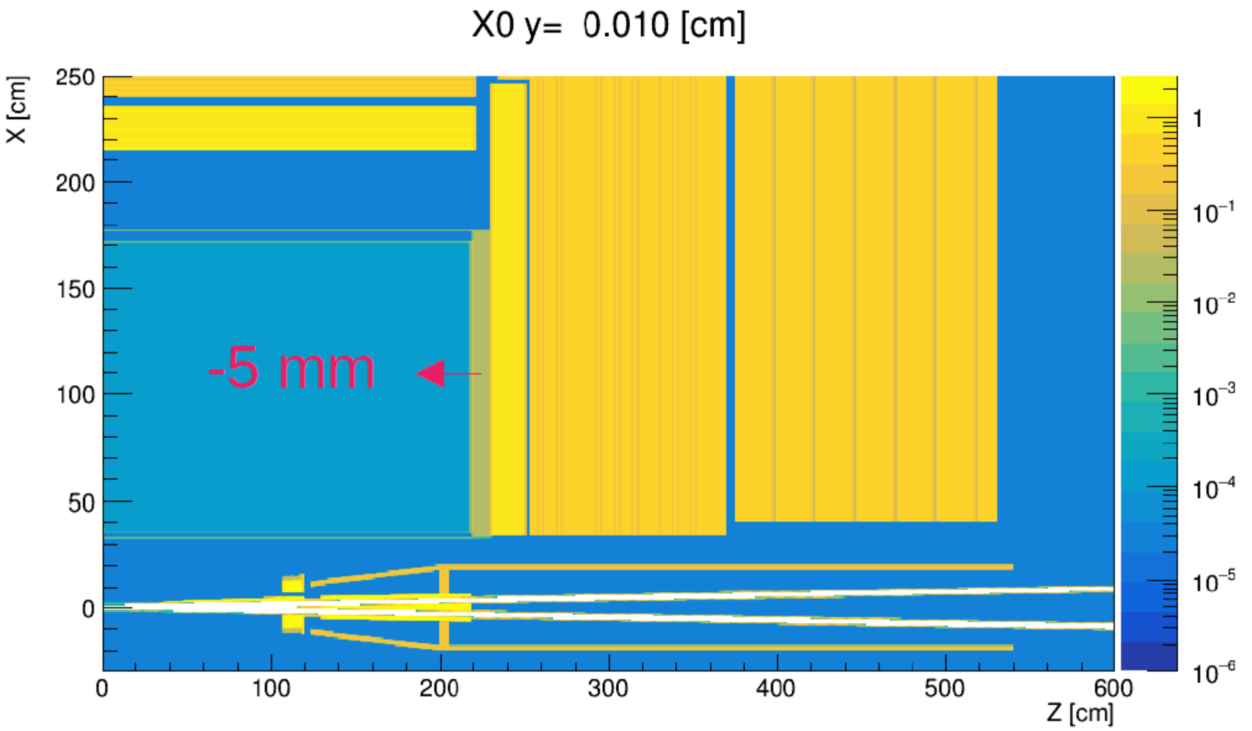


Ions produced by machine-related backgrounds

- Simulated these e+ e- pairs in some detector models
  - TPC only in 2T using CEPC size (Haoyu's talk tomorrow)
  - TPC only in 2T using ILD size (Daniel Jeans/KEK)
  - TPC only in 2T using FCCee size (Andrea Ciarma/CERN)
- Pass 100 bunch-crossings of bremsstrahlung pairs through G4-based full detector simulation
  - **"uniform" 2T B-field and no anti-DID**



TPC concept only in 2T field using ILD size



TPC concept only in 2T field using FCCee size

What about ions produced by machine-related backgrounds

- Distortions in r-phi due to ions from hadronic Z decays can be up to O(100) μm, but are stable to O(1) μm
- BUT, bremsstrahlung gives **~200X more** TPC primary ions than hadronic Z decays (**preliminary**)
- Anyway, **forward region plays a very important role** room for optimization
  - Some discussion and feedback to Haoyu and Manqi before this meeting

	primary ions / “event”	event rate	primary ions / 0.44 s “TPC frame*”
Z_had ILD_l5_v02 @ 2T	1.27M	54 kHz	30 $\times 10^9$
pairs ILD_l5_v02 @ 2T	75 k	33 MHz	1100 $\times 10^9$
pairs ILD TPC only @ 2T	15 k	33 MHz	220 $\times 10^9$
pairs FCCee w/ TPC	0.43 M	33 MHz	6200 $\times 10^9$

* maximum ion drift time in TPC = 0.44s

Some references of high luminosity e+e- collider

- High luminosity of e+e- collider
  - High luminosity challenging environment for TPC
  - Event overlap due to large drift times (30 μs) expected
  - At KEK, proposal to replace the drift chamber with **a tracking TPC**

	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	50			
Half crossing angle at IP [mrad]	16.5			
Luminosity per IP[10^{34}/cm^2/s]	8.3	26.6	191.7	0.8

FCCee lumi/IP @ Zpole: 182e34 cm^{-2} s^{-1}

bunch spacing: 30 ns → 33 MHz

sig_Z_{had} @ Zpole ~ 30nb = 3e-32 cm^2

int lumi/BX = 182e34 * 30e-9 = 5.46e28 cm^{-2}

#Z_{had}/BX = 5.46e28*3e-32 = 1.64e-3

rate of Z_{had} = 1.64e-3 * 33 MHz = 54 kHz

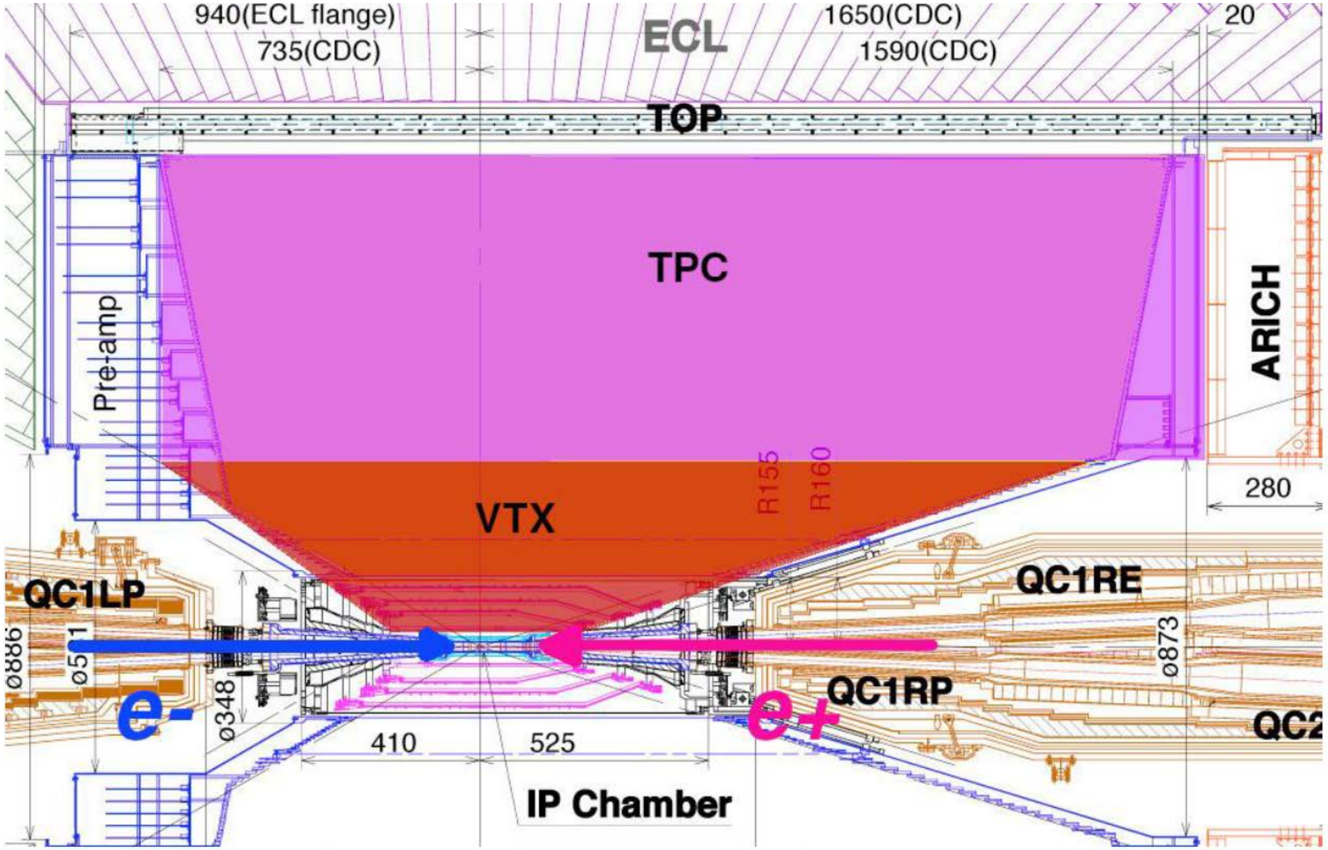
FCCee parameters of Tera-Z

- Asymmetric e^+e^- collider
  - electrons: 7 GeV
  - positrons: 4 GeV
- B-Factory by creating $\Upsilon(4S)$
- Design luminosity (at time of thesis)

$$\mathscr{L} = 6.5 \times 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

- Top-up injection scheme

SuoerKEKb parameters of High luminosity



TPC concept proposal at KEK

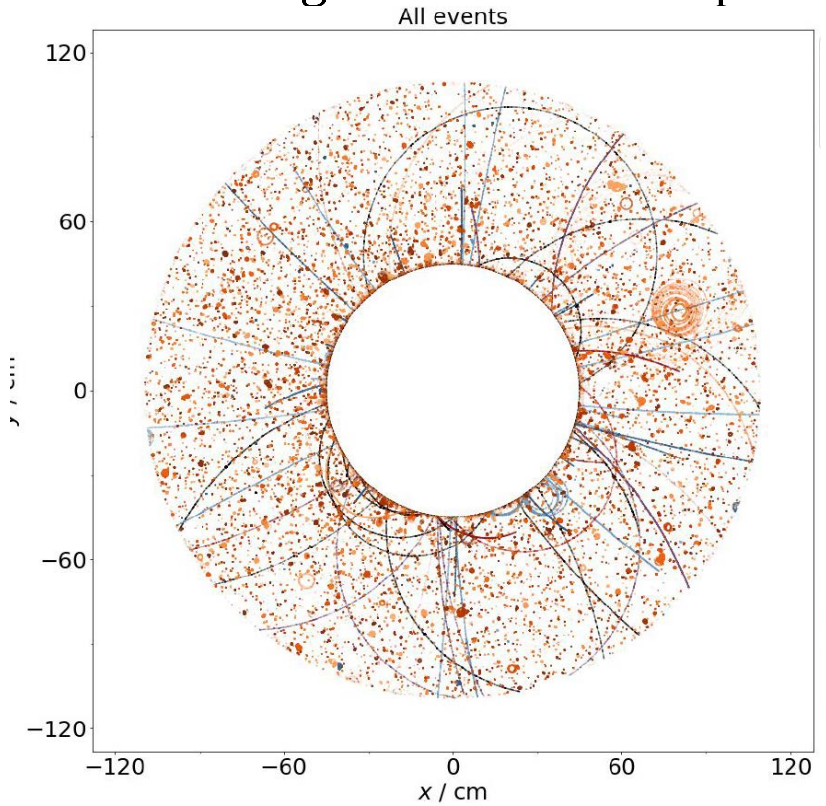
Beam background of KEKb

- **Touschek Scattering**
  - Scattering of two beam particles within one bunch
- Coulomb/Beam-gas Scattering
- Elastic Coulomb scattering of beam particles with residual beam gas
- **Bremsstrahlung**
  - Inelastic scattering of beam particles with gas nuclei
- **Injection Backgrounds not included!**
  - Betatron-oscillating injection particles lost in interaction region due to strong magnetic fields of focusing magnets

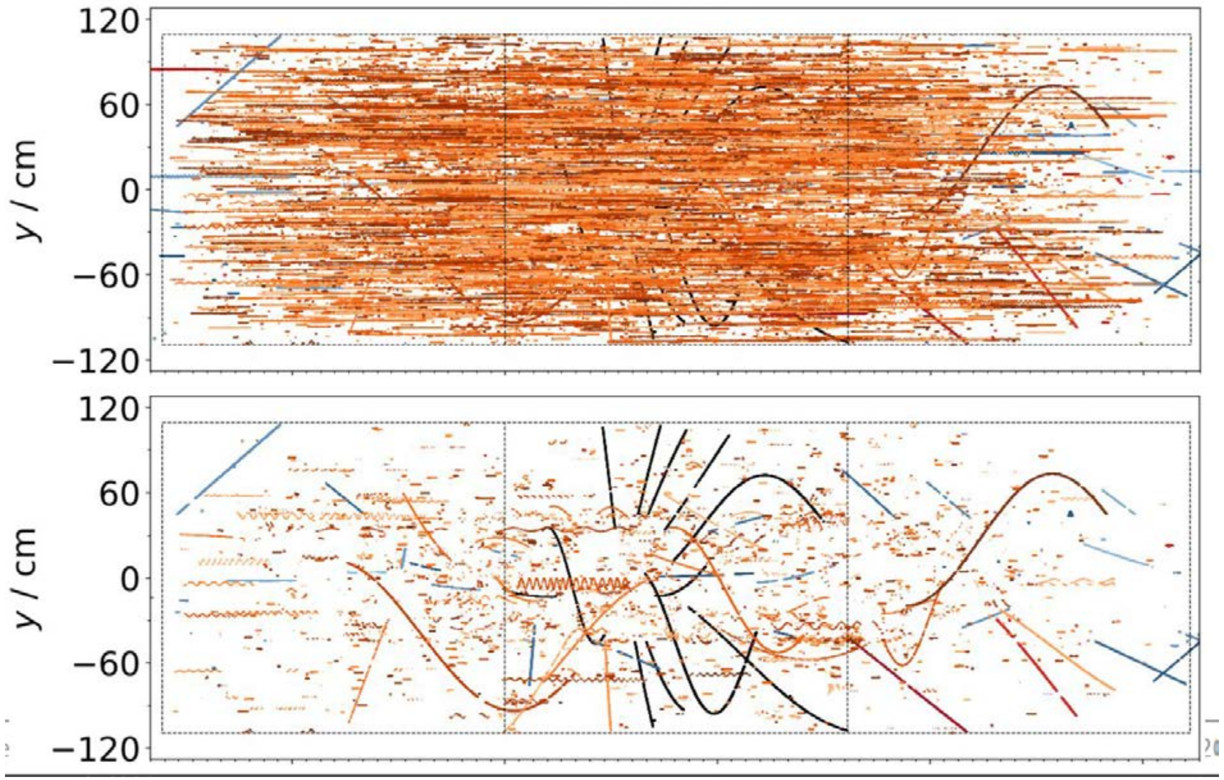
Process	Rate / MHz	Rate / $(60\mu s)^{-1}$
Brems HER	2.46479	147.89
Brems LER	8.2928	497.57
Coulomb HER	16.335	980.10
Coulomb LER	191.641	11498.46
Touschek HER	0.242353	14.54
Touschek LER	119.409	7164.54

Beam background rejection

- **Beam background mainly produces micro-curlers**
- Easy to identify
  - Horizontal in z
  - Isolated clump in x-y
- Use pattern recognition algorithm for identification and rejection: **Bkg rejection efficiency > 90%**
- Track finding also need to be optimized



Including Beam Background



Background Rejection

Open question: to be addressed by R&D

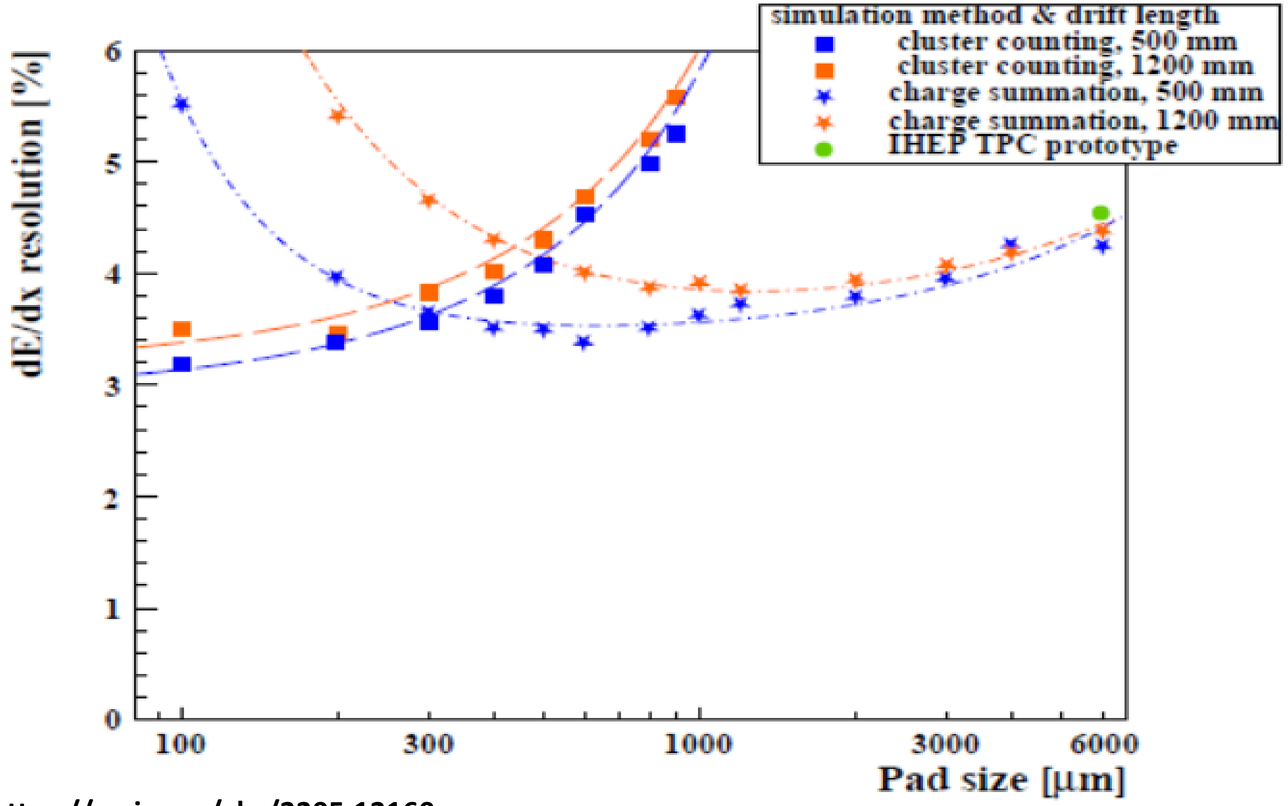
- **High Luminorsity operation (2×10^{36}) @ Z with 2 T B-Field**
- Shield and mask should be optimized in MDI region (only for TPCs)
    - Bremsstrahlung gives **~200X more** TPC primary ions than hadronic Z decays ?
    - Use pattern recognition algorithm for identification and rejection ?
    - Backgroud rejection efficiency ?
    - ...

- **Pixelated readout TPC is promising, compared to Pad readout**
    - Material budget, construction cost, power & cooling, Occupancy is OK
    - Lower Ion backflow at low gain (to be addressed by R&D)
    - Potential for dN/dx, essential for PID
    - …

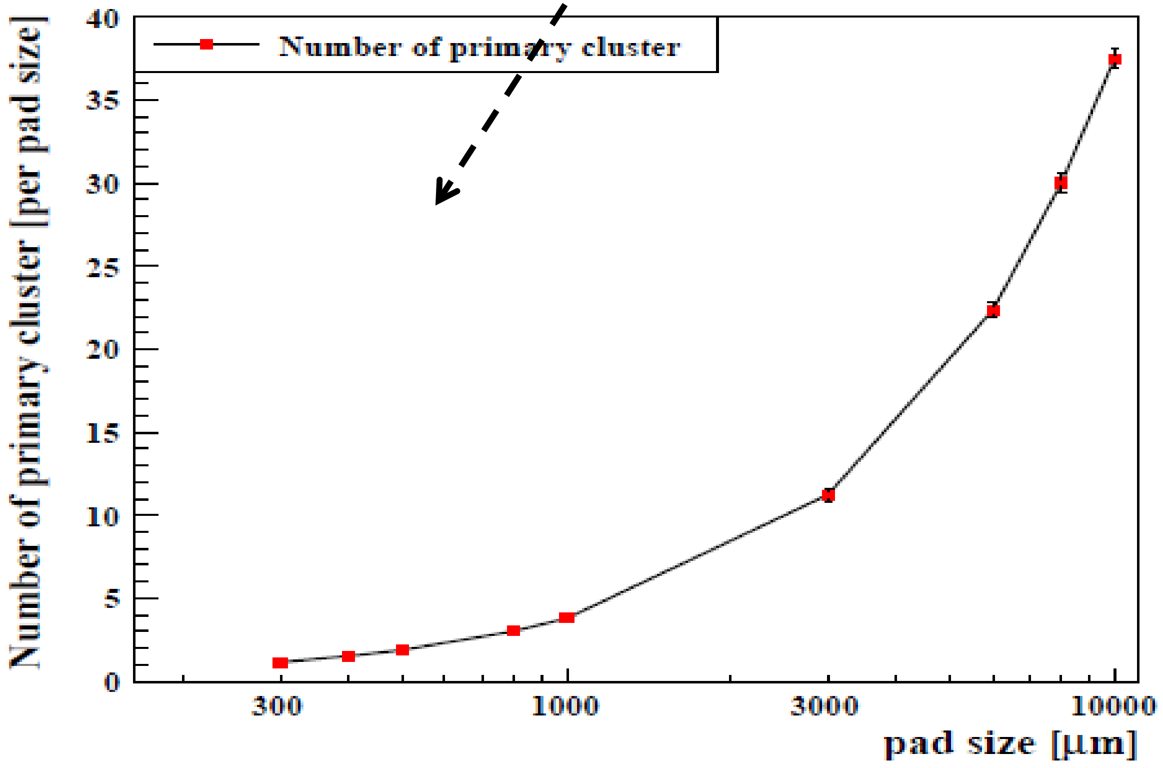
- Toward pixelated readout TPC technology

High granularity for improved PID in TPC

- Current full ILD reconstruction: 6mm pads → **~4.8% dE/dx resolution**
- Smaller pad size improved momentum resolution via dE/dx and dN/dx → Pad toward pixel pad
- Smaller pad size improved the voxel occupancy (10^{-4} level)
  - Pad size of about 300μm can record **~1 primary cluster along track length** at T2K gas
  - High **readout granularity** VS the primary cluster size optimization



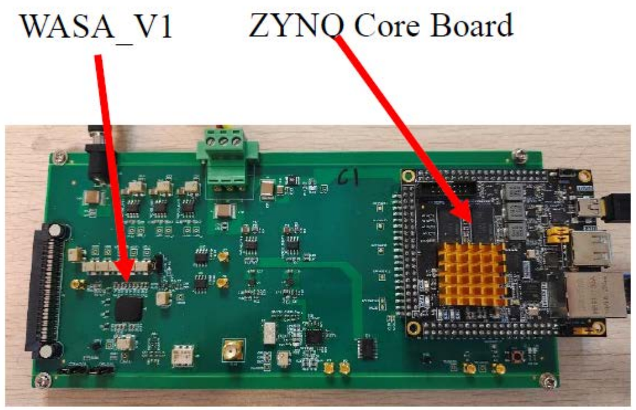
Simulation of the primary cluster along the drift length

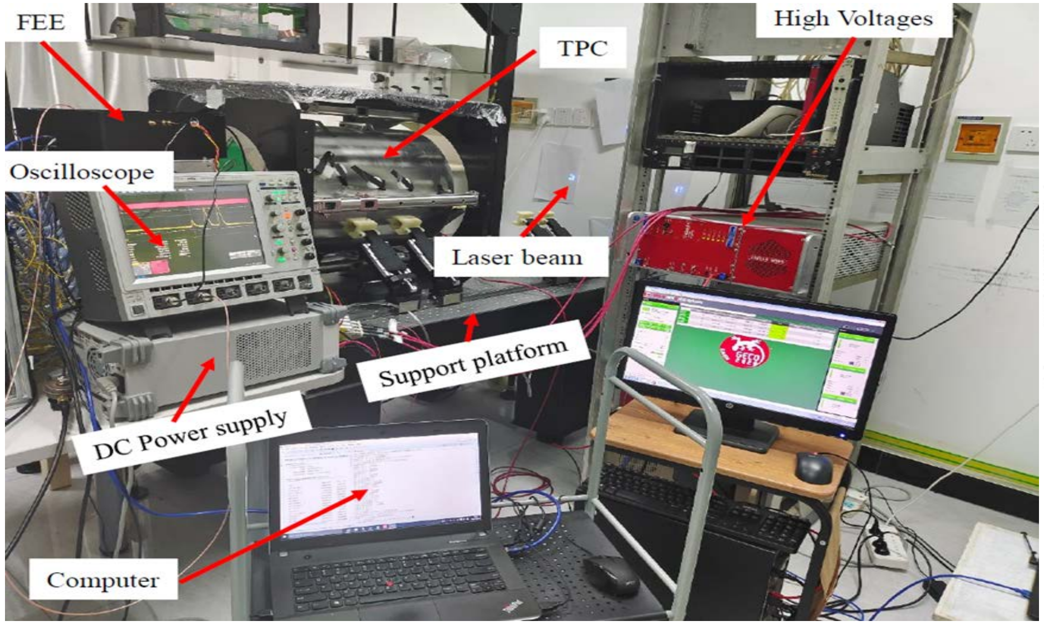


https://arxiv.org/abs/2205.12160

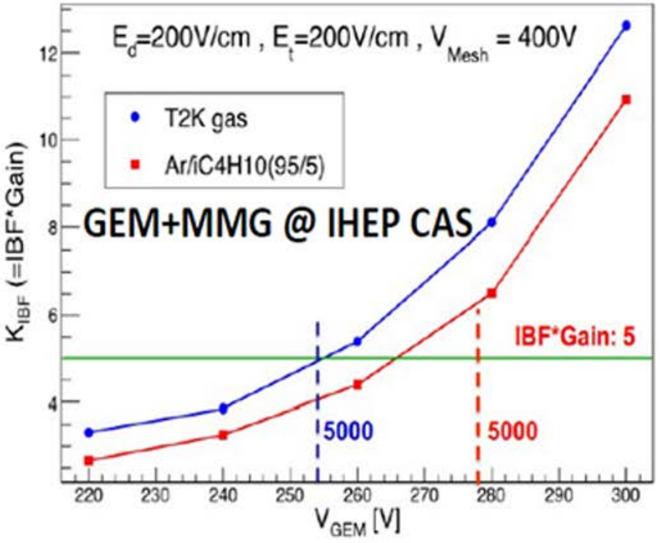
CEPC TPC detector prototyping roadmap at IHEP

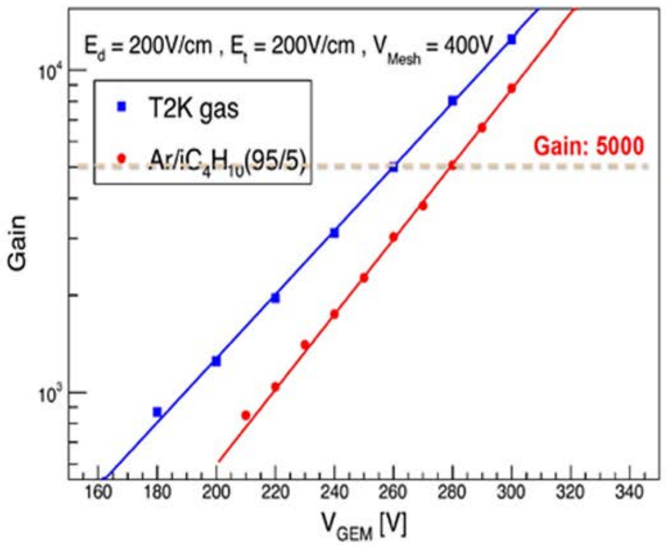
- From TPC module to TPC prototype R&D for beam test
  - Low power consumption FEE ASIC (**reach <5mW/ch** including ADC)
- Achievement by far:
  - Supression ions hybrid GEM+Micromegas module
    - IBF×Gain **~1 at Gain=2000** validation with GEM/MM readout
  - Spatial resolution of **$\sigma_{r\varphi}\leq 100\ \mu m$** by TPC prototype
  - dE/dx for PID: <4% (as expected for CEPC baseline detector concept)





Low power consumption readout

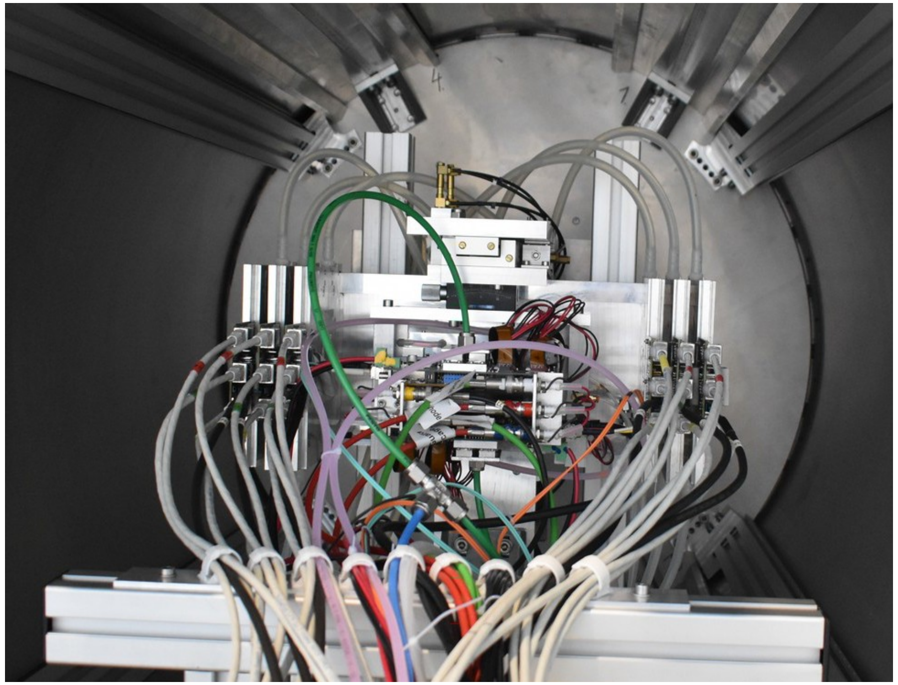


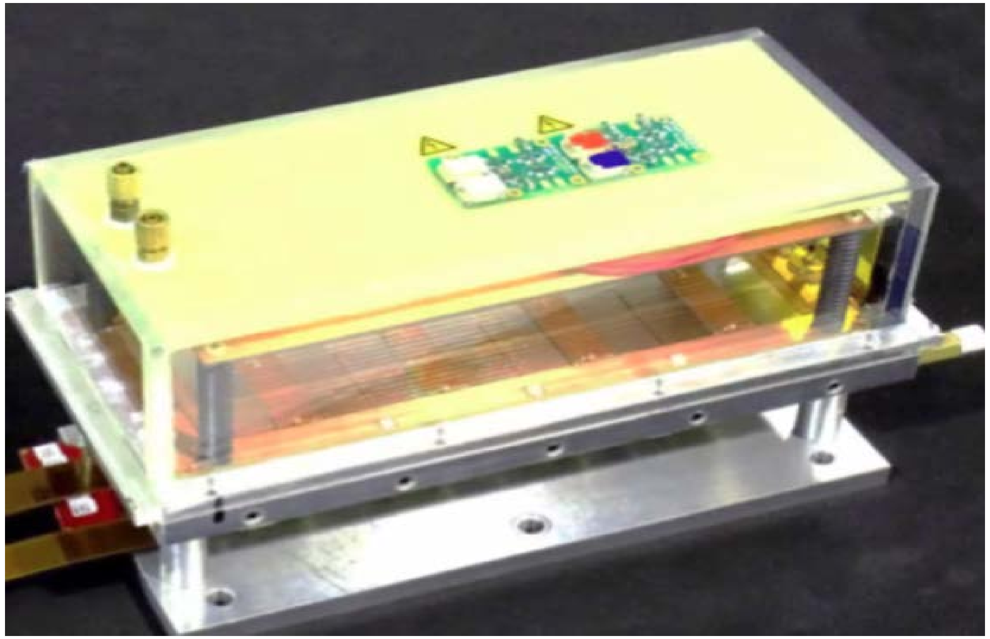


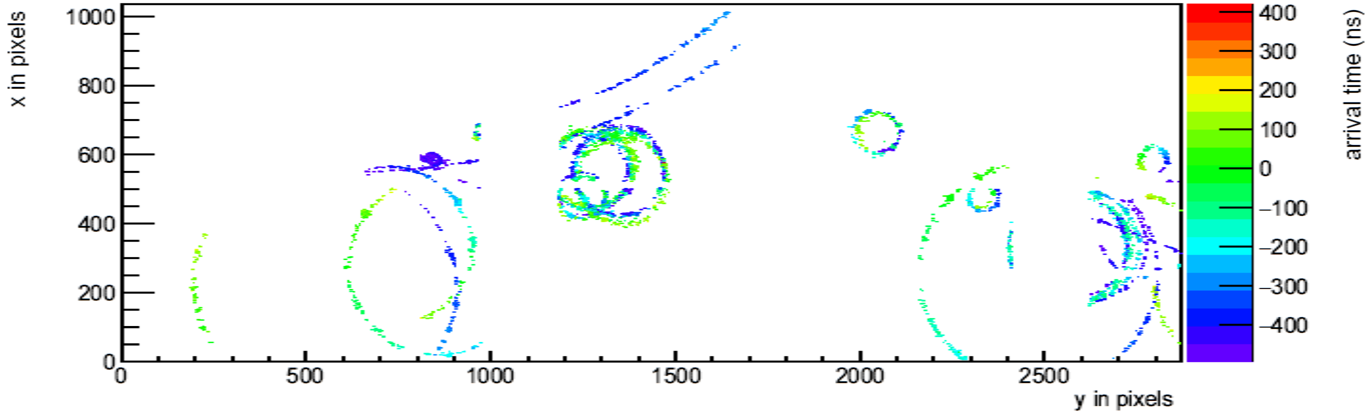
GEM+Micromegas module R&D

Pixelated TPC technology – Large scale readout from LCTPC

- Pixelated TPC prototype with GridPixes:
  - 8-QUAD module (2x4 quads) with field cage
    → 8-Quad GridPixes covered **an active area of 39.6×28.4 cm²**
  - ~**100-120 chips/module** 240 module/endcap (full size 10m²)
    → 50000-60000 GridPixes
- During the test beam ~10^6 events were successfully collected, all results showed that **a pixel TPC is realistic.**



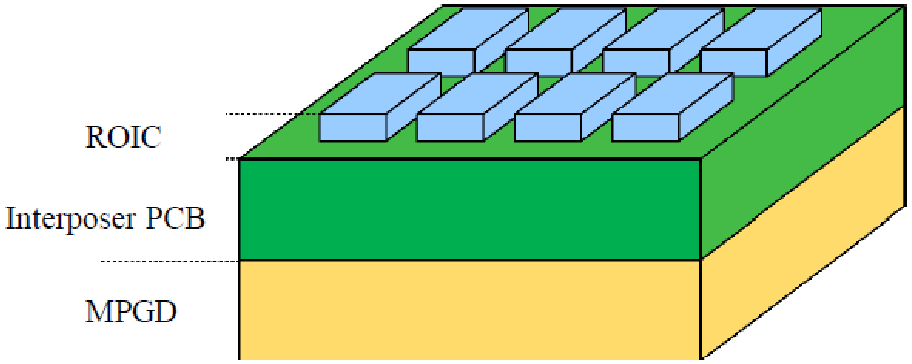




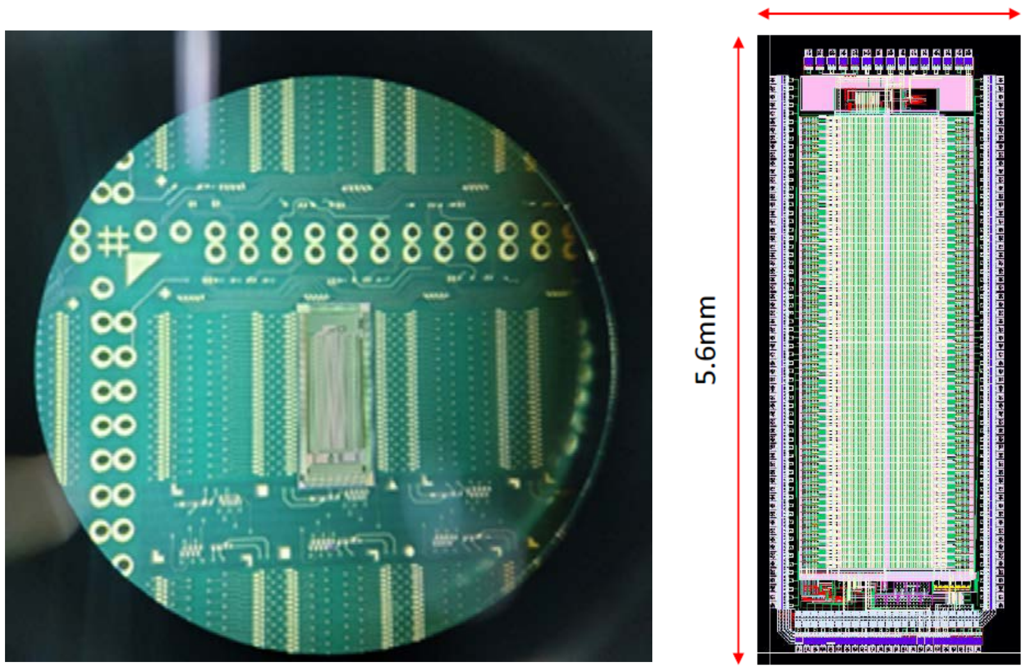
DESY testbeam in June 2021

Current R&D effort: Pixelated TPC R&D from CEPC

- **R&D on Macro-Pixel TPC readout for CEPC**
  - Macro-Pixel TPC ASIC chip was started to developed in this year and **1st prototype wafer has done in last year**.
  - The first version ROIC has been received and under testing.
  - The **TOA and TOT** can be selected as the initiation function in the ASIC chip.
    - 1mm×6mm → 500μm×500μm pixel readout
    - Higher precision and higher rate (MHz/cm^2)
    - Gain of the amplification: >40mV/fC
    - Channels: 128
    - Time resolution: **14bit** (5ns bin)
    - Time discriminator: TOA (Time of Arrival)
    - **Power consumption: <1mW/pixel (1st prototype)**
      - **~400mW/cm^2**
      - **100mW/cm^2 (Goal and final design)**
    - Technology: 180nm CMOS -> 60nm CMOS
    - High metal coverage: 4-side bootable



Principle of Macro-Pixel TPC readout



1st readout PCB board and the ASIC layout

Summary

- **In CEPC TPC study group, the updated R&D of MDI for TPC technology focused on the ions in the chamber, the forward region will be a very important role room for optimization at the high luminosity e+e- colliders. The shield/mask should be very carefully to consider in MDI region for all of inner detectors.**
- **TPC detector module and prototype using the pad with integrated 266nm UV laser tracks have been developed for the future e+e- colliders. Updated R&D will be from pad size readout toward pixel pad size readout, and the new readout chip has been developed and commissioned.**
- **Synergies with CEPC/FCCee/EIC/LCTPC allow us to continue R&D and ongoing, we learn from all of their experiences.**

Many thanks!