Status of Pixelated and Pad Readout TPC Technology R&D for Future e^+e^- Collider

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On behalf of CEPC TPC study group and Special thanks to LCTPC collaboration

Physics and Detector mini-workshop, February 12-13, 2023, HKIAS

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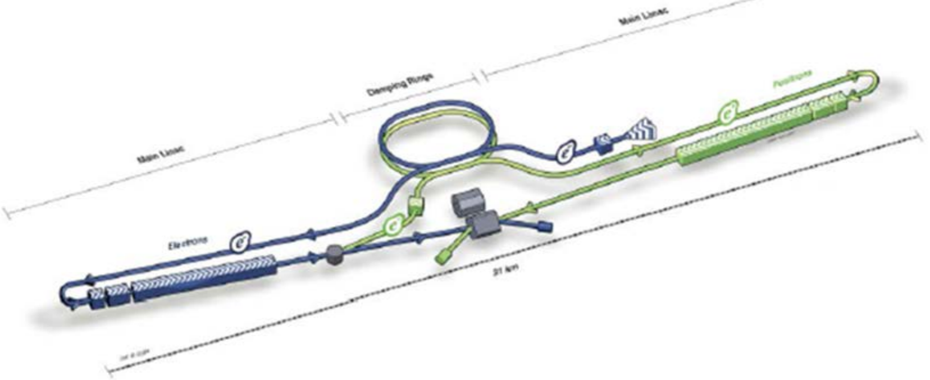
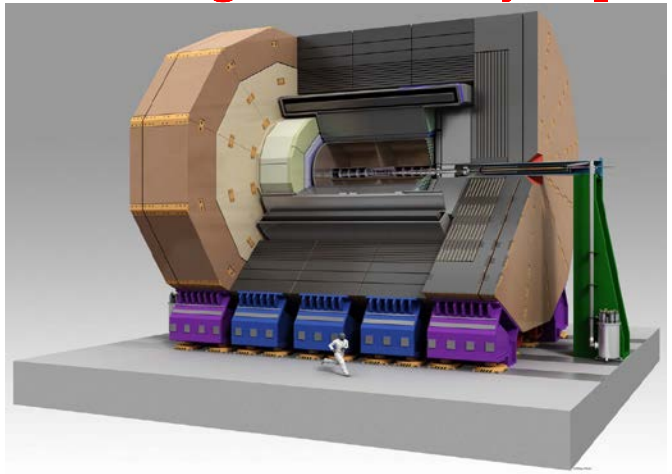
- **Summary**

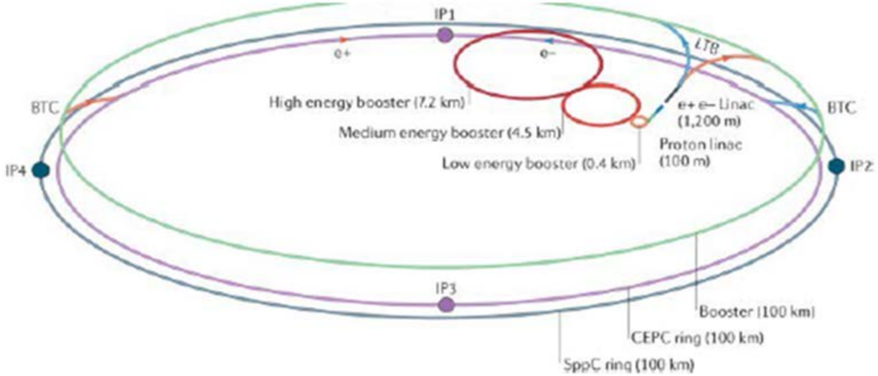
TPC technology for the future e+e- colliders

- A TPC is the main tracking detector for **some candidate experiments at future e+e- colliders**
  - The baseline detector concept of ILD and CEPC
  - TPC can provide hundreds of hits (for track finding) with high spatial resolution compatible with PFA design (**very low material** in chamber)
- TPC technology R&D from **Higgs run to High luminosity Z pole run** at future e+e- collider

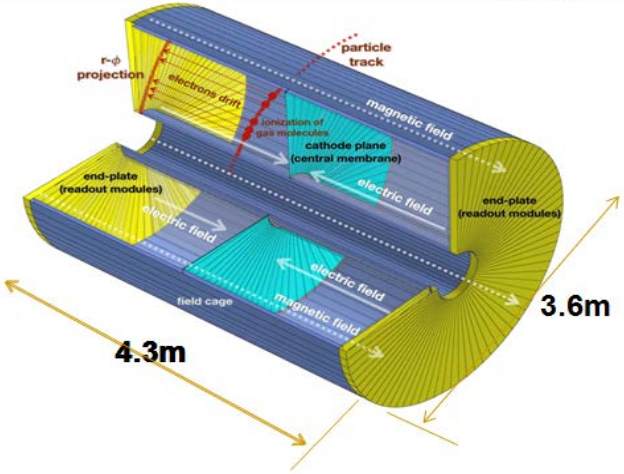


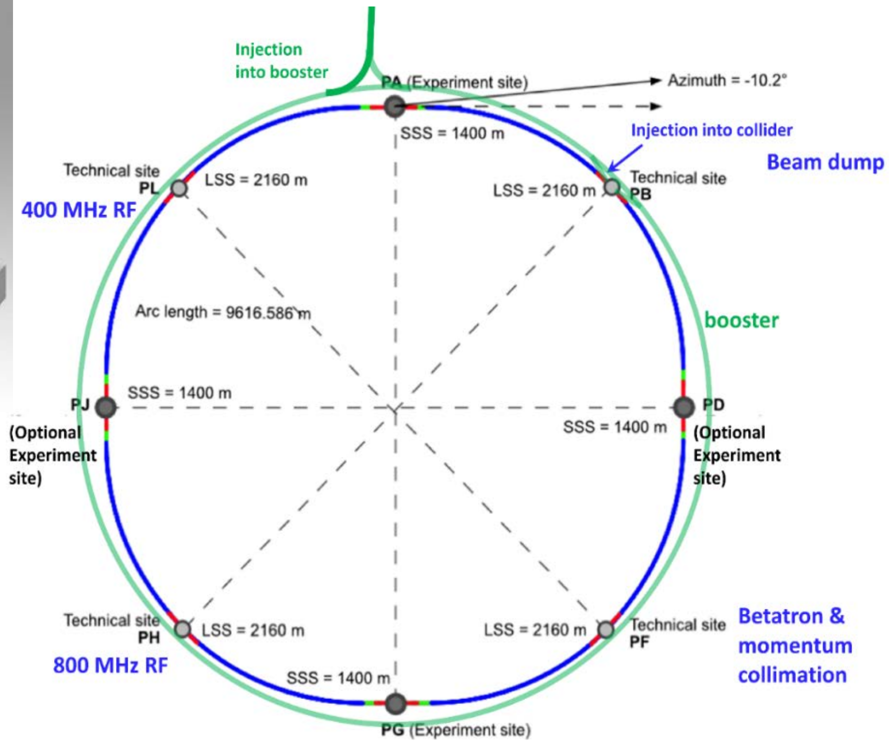
International Linear Collider (ILC)





Circular Electron Positron Collider (CEPC)





Future Circular Collider (FCC-ee)

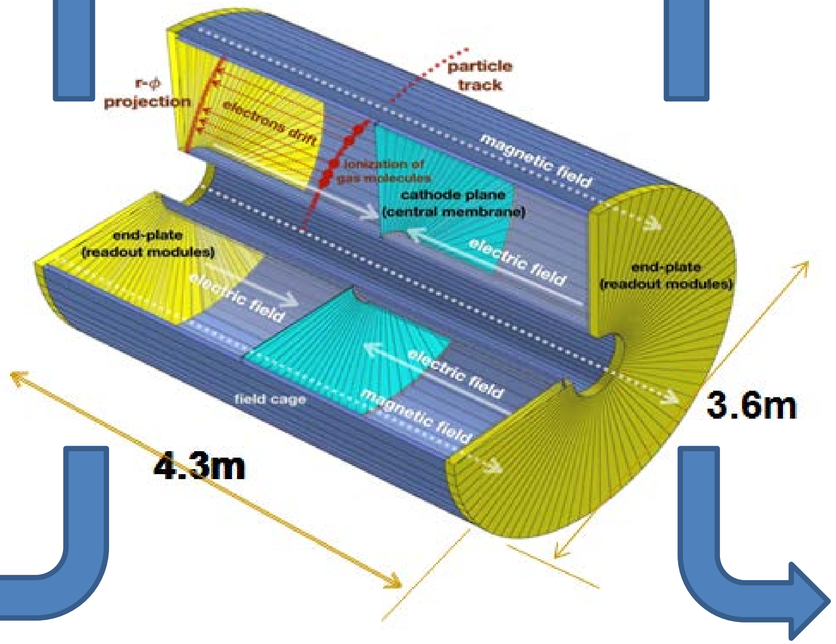
https://arxiv.org/abs/2203.06520

Key issues of TPC technology for e+e- collider

TPC track detector for e+e- collider

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

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

Need investigation of the electrons/ions density at CEPC

- Simulation results based on CEPC's parameters (**High luminosity at Z pole: 10^{36}**)
- 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%)**

See Paul 's talk on 12th, Feb. mini-workshop

Electric field analysis

Cylindrical coordinates

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

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

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

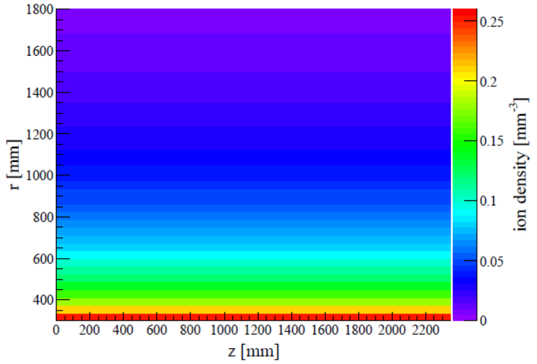
$$\Phi_m(r,k) = K_m(kr) \int_0^r R_m(r',k)\, I_m(kr')\, r'\, dr' + I_m(kr) \int_r^{\infty} R_m(r',k)\, K_m(kr')\, r'\, dr'$$

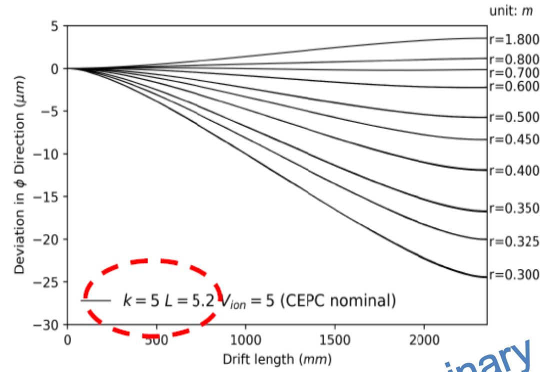
$$R_m(r',k) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \rho_m(r',z')\, e^{-ikz'}\, dz'$$

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

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

Ions density in chamber

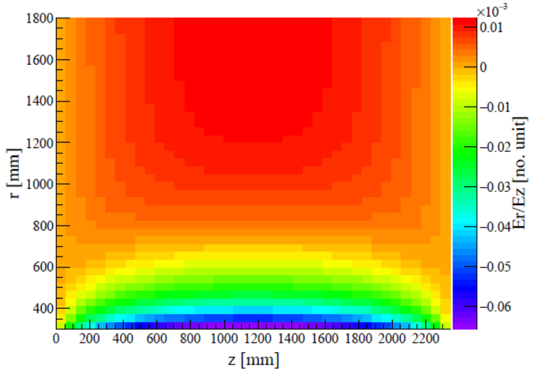


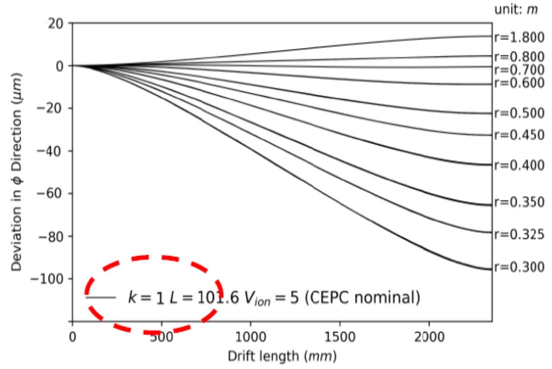


E_r/E_z

Z

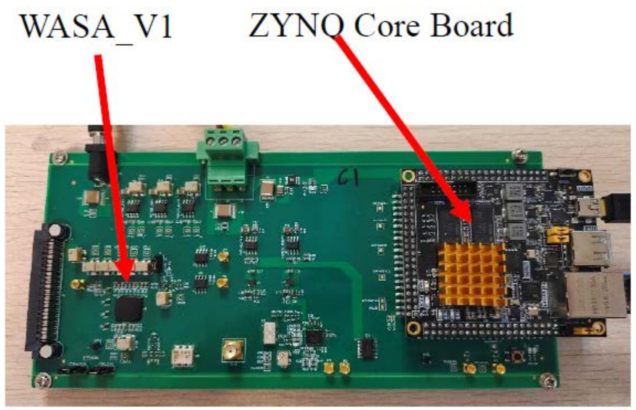
Preliminary

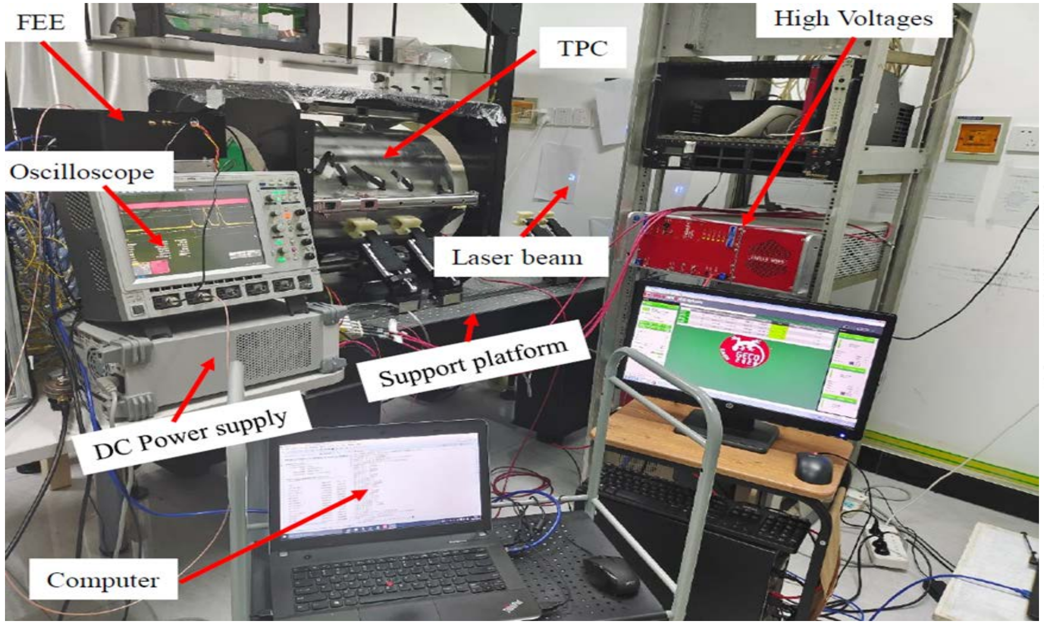




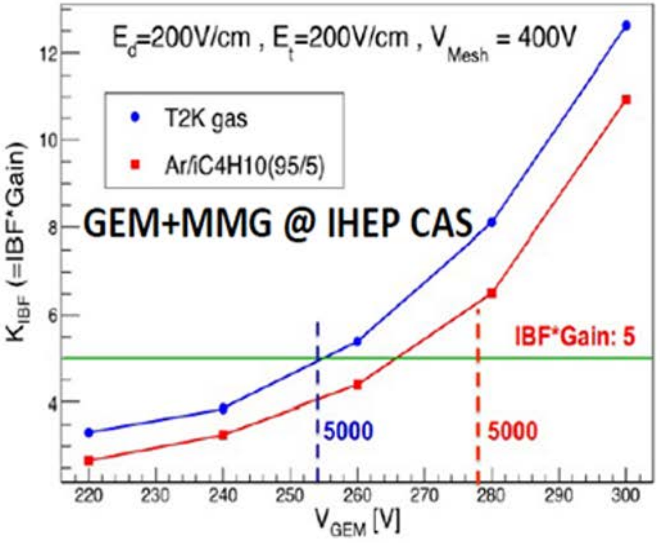
CEPC TPC detector prototyping roadmap

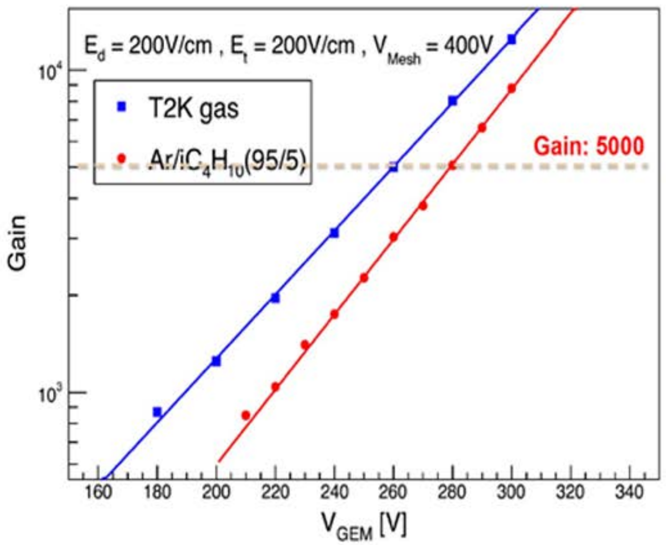
- From TPC module to TPC prototype R&D for beam test
  - Low power consumption FEE ASIC (**reach <5mW/ch** including ADC)
- Achievement by far:
  - Supression ions hybrid GEM+Micromegas module
    - IBF×Gain **~1 at Gain=2000** validation with GEM/MM readout
  - Spatial resolution of **$\sigma_{r\varphi}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





Low power consumption readout





GEM+Micromegas module R&D

- Pad TPC prototype integrated with UV light

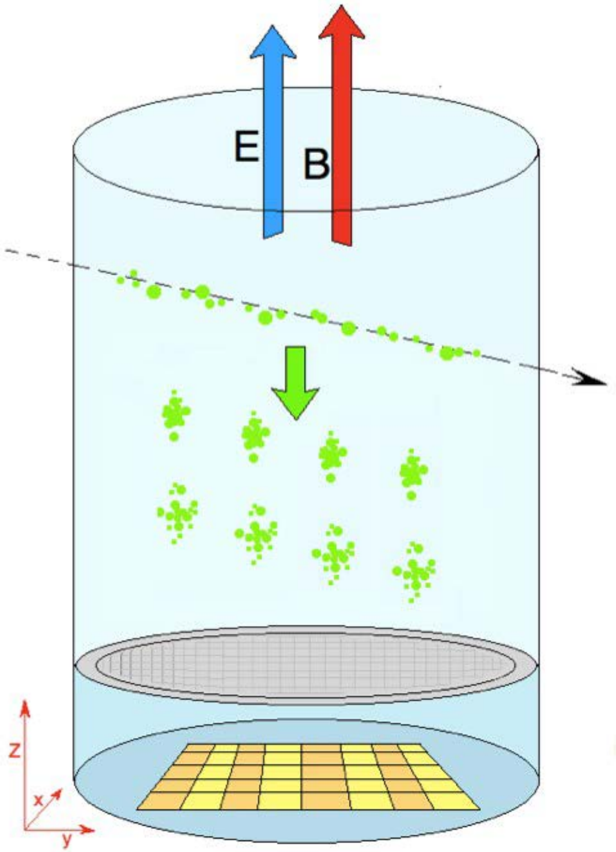
How to create stable tracks and massive electrons in the chamber?

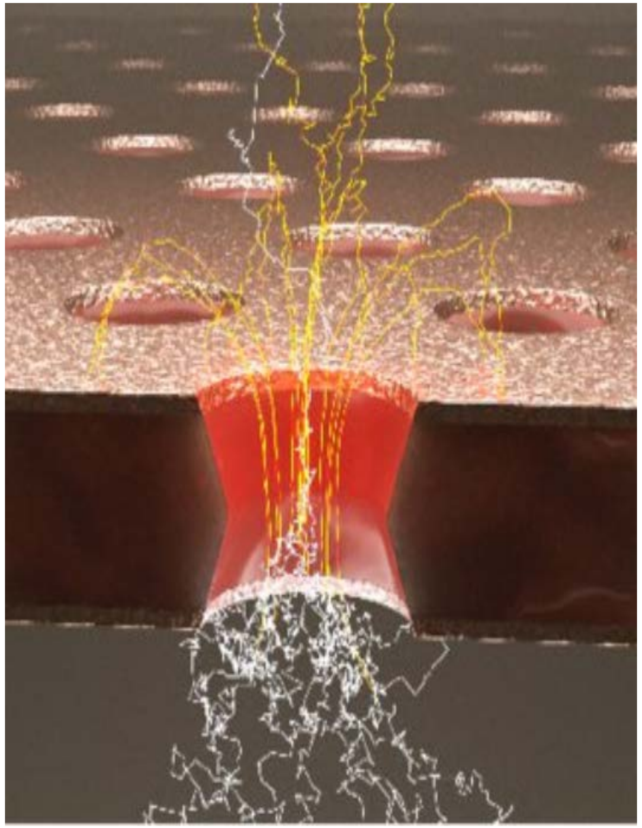
Indirect method to generate electrons

- ^{55}Fe source, X-ray tube, synchrotron radiation
- Electron beam
- MPGD detector multiplication method
- Discharge, Ions back flow on the small area

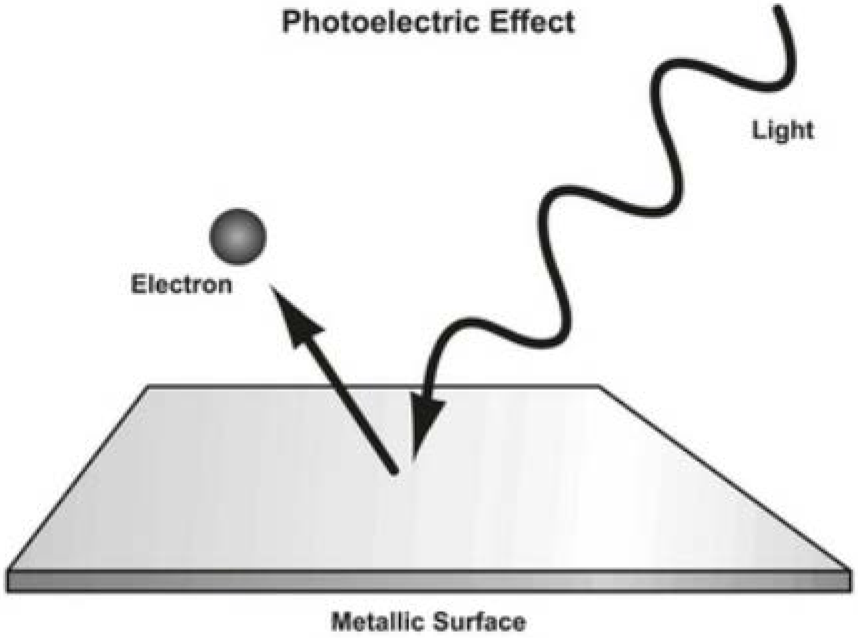
Direct method to generate primary electrons

- Created the massive electrons on big area
- **Photoelectric effect** method **(<10uJ/cm²)**
- **Two-photon ionization** method **(>10uJ/cm²)**





Indirect method



Direct method

UV laser: Two-photon ionization method (>10uJ/cm^2)

- Some gas can absorb the energy of 2 photons from UV laser and ionized
- Wavelength of UV laser: 266nm (almost: 4.66eV × 2)
- Threshold of the ionization energy: **>10uJ/cm^2 @MIP**
- **To mimic the stable laser tracks in chamber**

UV Laser TPC prototype R&D
Without B field

UV light: Photoelectric effect method (<10uJ/cm^2)

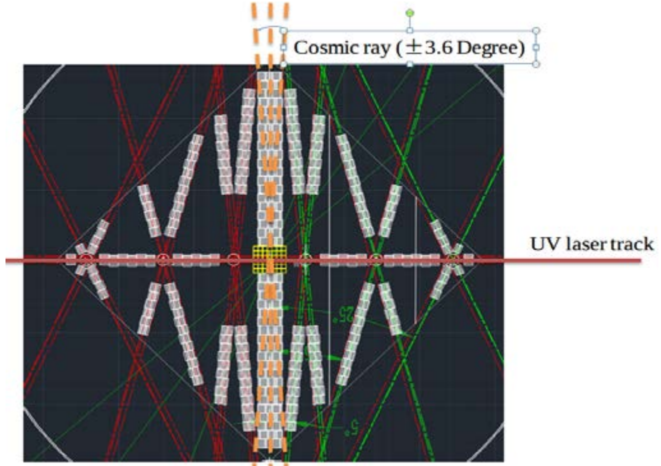
- Explanation of photoelectric effect by A.Einstein
- Each photon carries energy proportional to its frequency $E_\gamma = hf = hc/\lambda$
- One electron absorbs only one photon
- Energy of UV can less than 10uJ/cm^2
- **To study of the stable current of photoelectric**

Massive electrons R&D
Without influence working gas

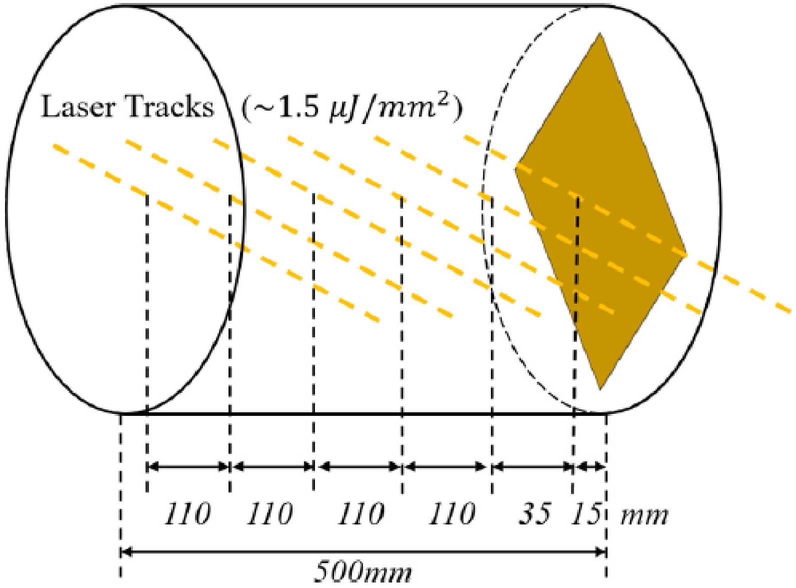
Study the deviation of the tracks
under the high luminosity

Design and commission of TPC prototype with 266nm UV laser tracks

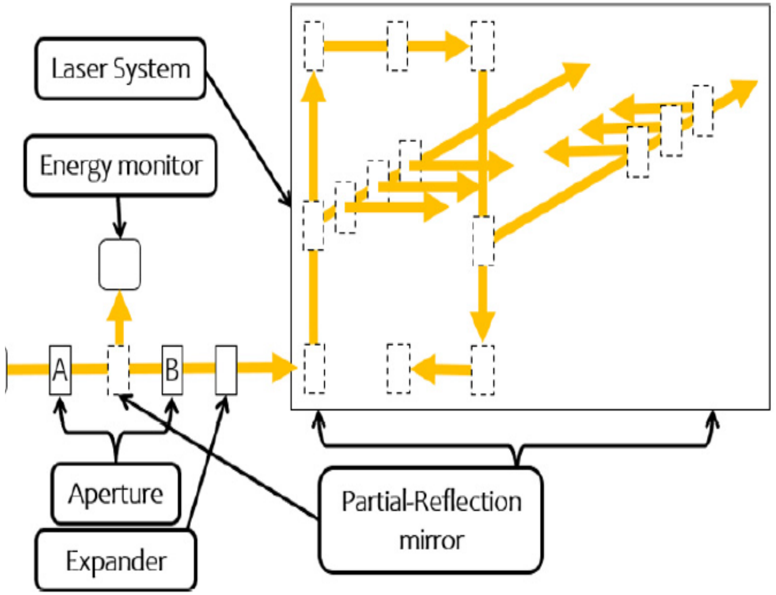
- TPC prototype with separately 6 horizontal laser tracks is designed along the drift length of 500mm
- Effective area of 200mm×200 mm using **1mm×6mm pad readout size**
- Precision value of UV laser's stability **can meet TPC prototype's physical requirement <3.2 μm**
- The laser ionization should be similar to **1-2 MIPs**, which can generate **100-200 electrons** per centimeter in an argon-based gas (**optimization of the laser energy density**)



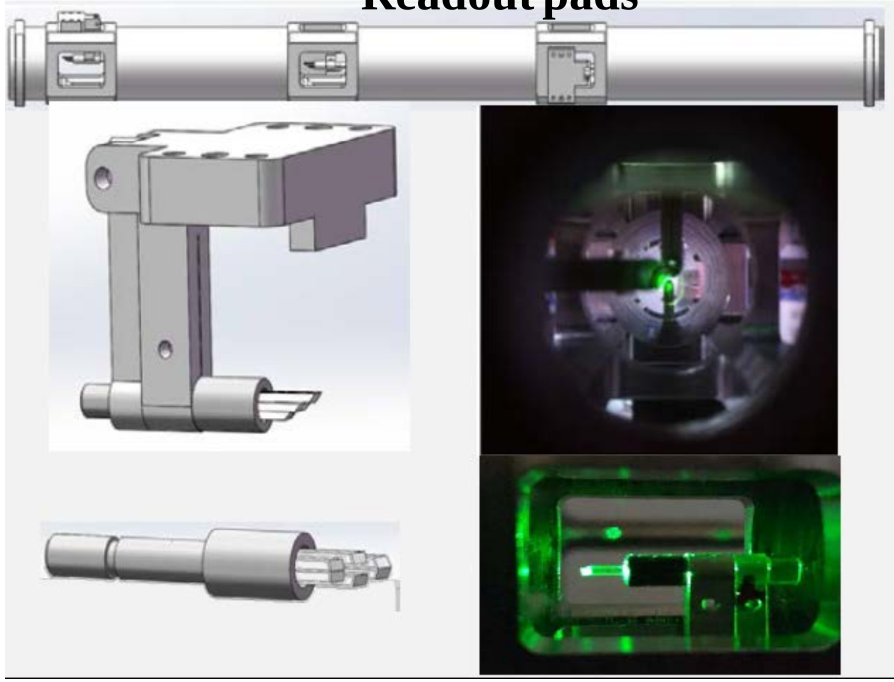
Readout pads



Laser tracks along the drift length



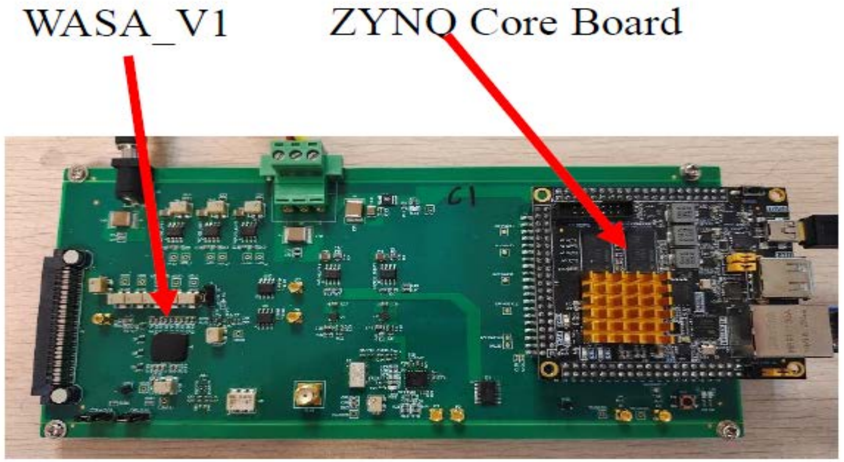
UV laser tracks mapping



UV laser mirror system

Low power consumption readout ASIC R&D

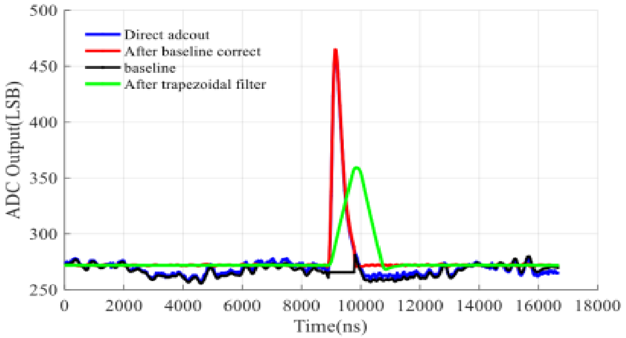
- WASA V1 has been developed: 16 channel AFE+ADC+LVDS data output
- Total power consumption **with ADC function: ~2.4 mW/ch**
- Tested with TPC detector using 128 channels at IHEP

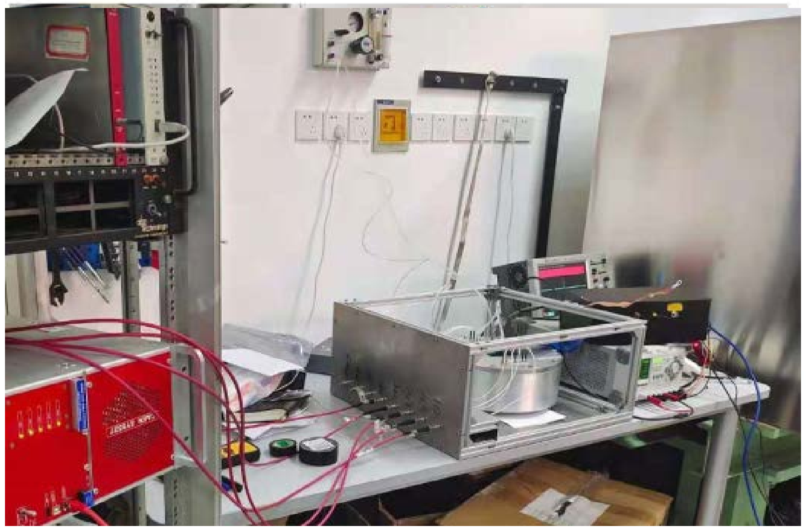


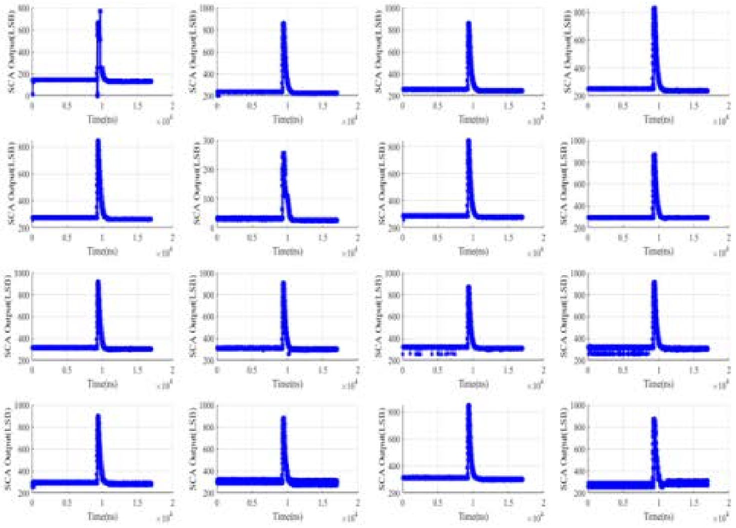
^{55}Fe testing

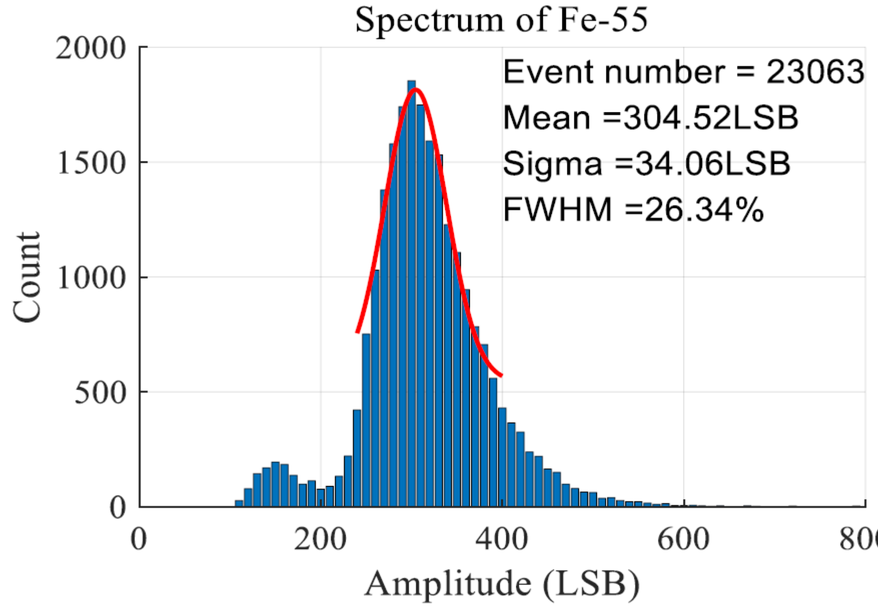
Testing parameters:

- GEMs detector: 280V-310 V
- E_{drift}: ≤280 V/cm
- Operation gases: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- Radioactive source: ^{55}Fe@ 1mCi
- Successfully commissioned and collected signals using DAQ





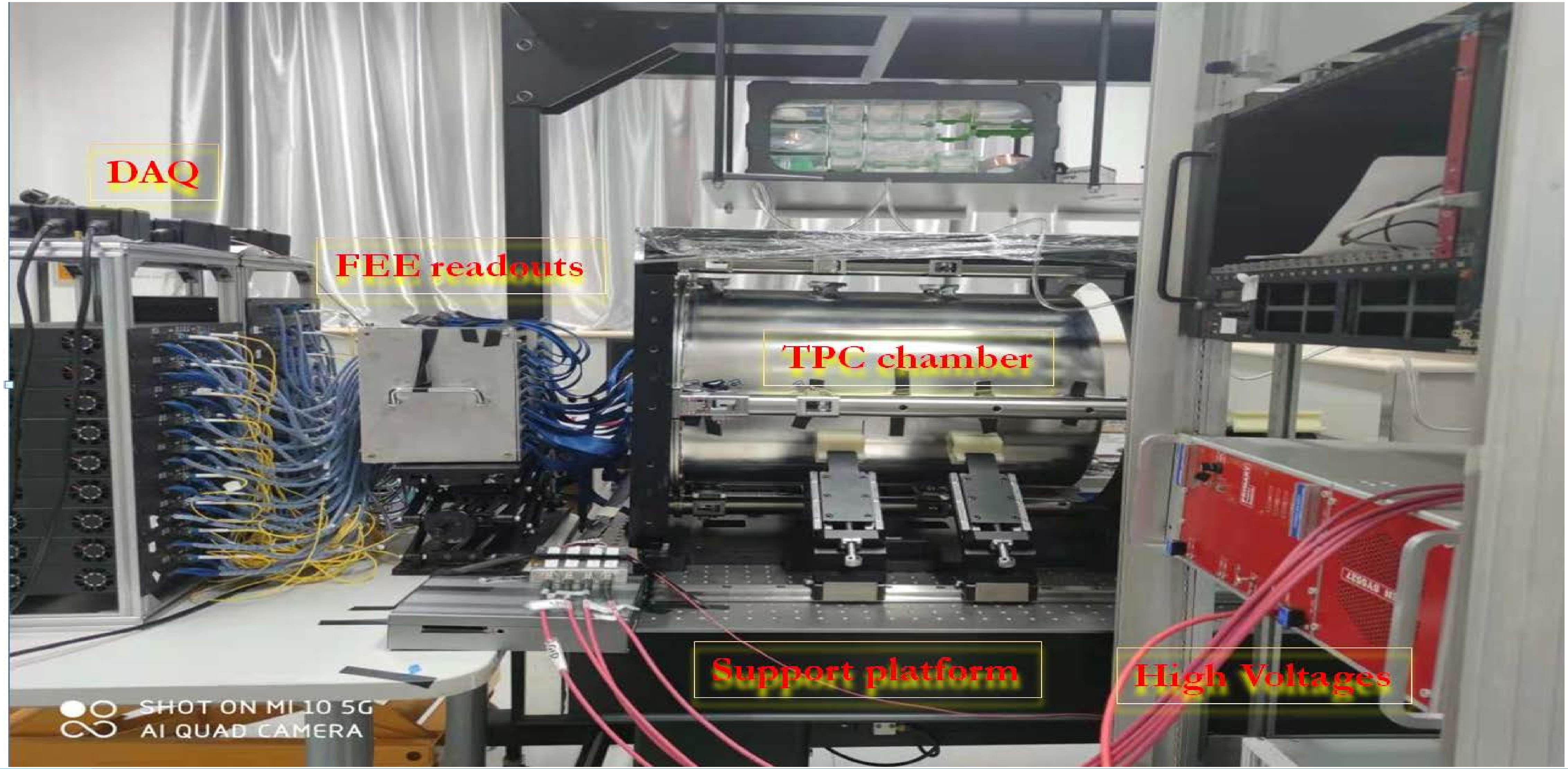




https://doi.org/10.1088/1748-0221/15/05/P05005

Development of Pad TPC prototype

- Successfully to develop the TPC prototype integrated UV laser tracks at IHEP, CAS
- Experimental studies of the **spatial resolution, dE/dx resolution** achieved with the pseudo-tracks

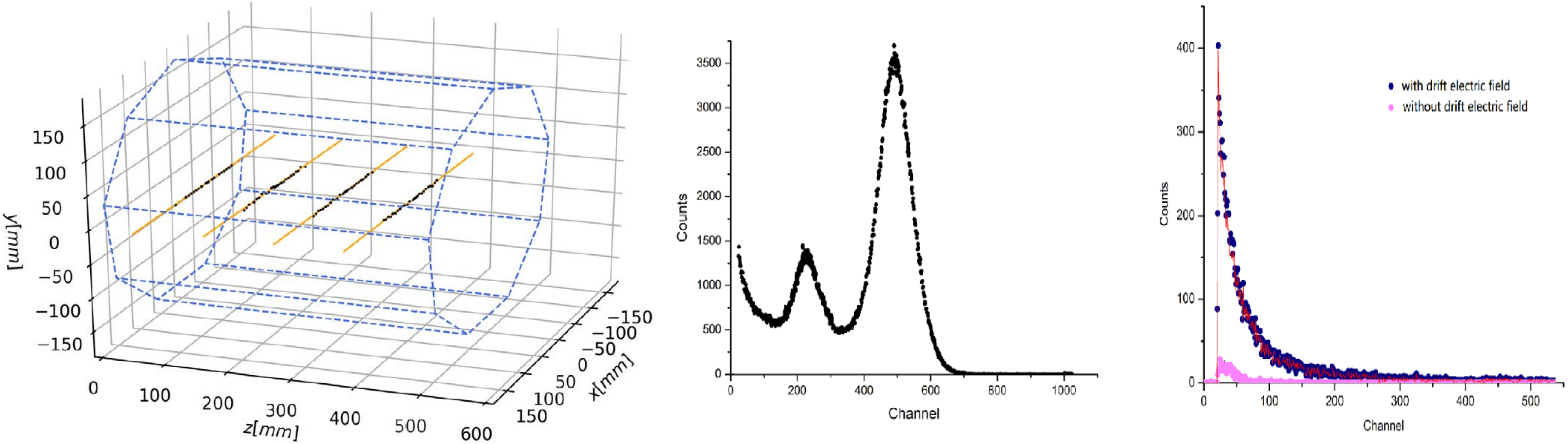


Reconstruction event and energy spectrum of ^{55}Fe/Cosmic ray

- TPC detector prototype can study the UV laser track, 55Fe radiation source and the cosmic ray.
- TPC prototype was checked after one year development
  - ^{55}Fe X-ray spectrum profile is very good
  - **Detector gain just shift 2% than one year before.**
- The Landau distribution of the cosmic ray's energy spectrum was successfully obtained.

Summary of the event selection cuts.

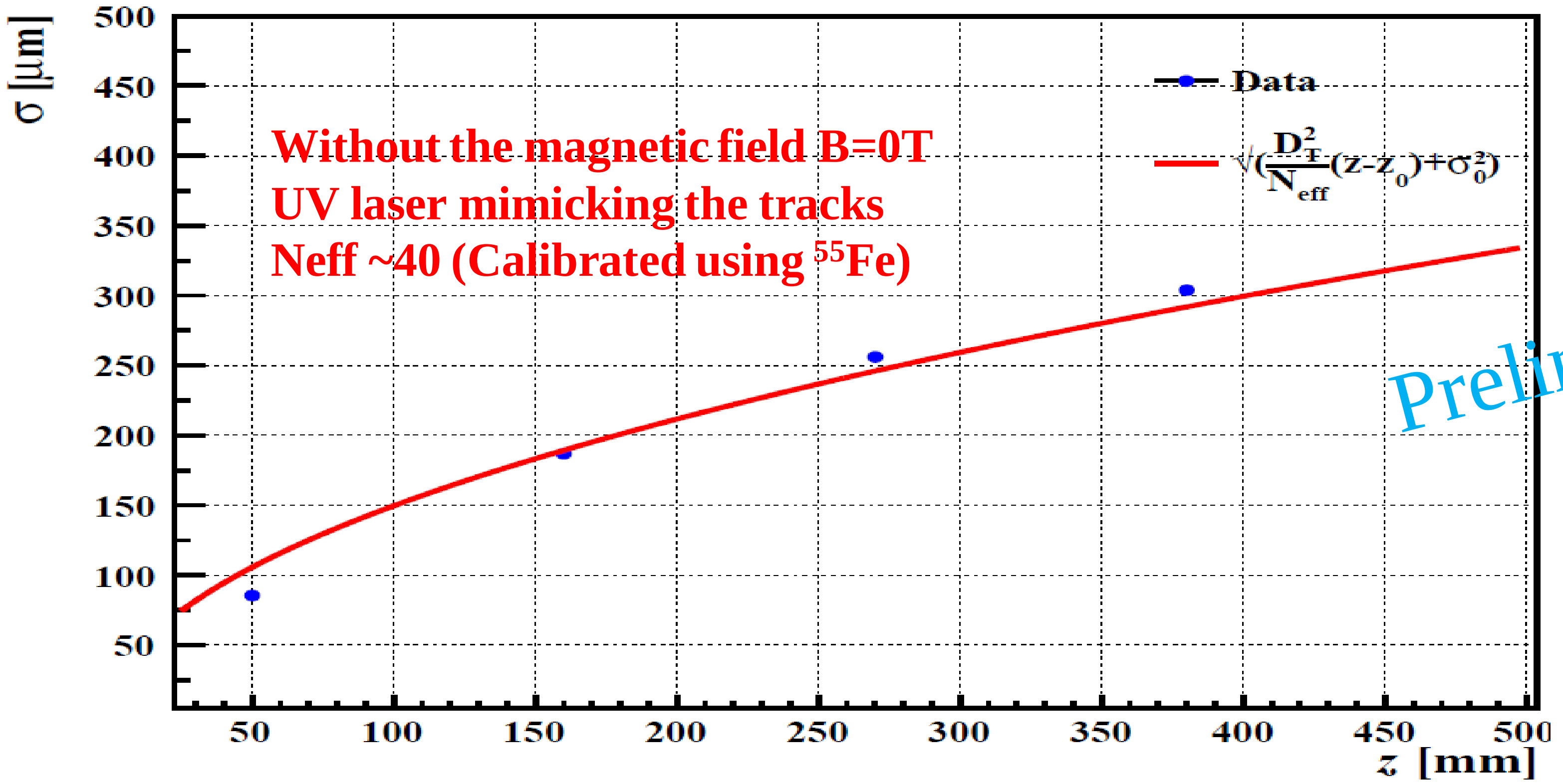
Laser energy monitor	Variation range	$E_{mean} \pm \sigma$
TPC detector	Hit ToA	layer#1 2.6 ~ 2.9 μs layer#2 5.7 ~ 6.0 μs layer#3 8.2 ~ 8.5 μs layer#4 10.5 ~ 11.0 μs
	Trigger pads	≥ 2 for each column
Laser and detector	The laser control chassis triggers the energy monitor and DAQ system at the same time.	

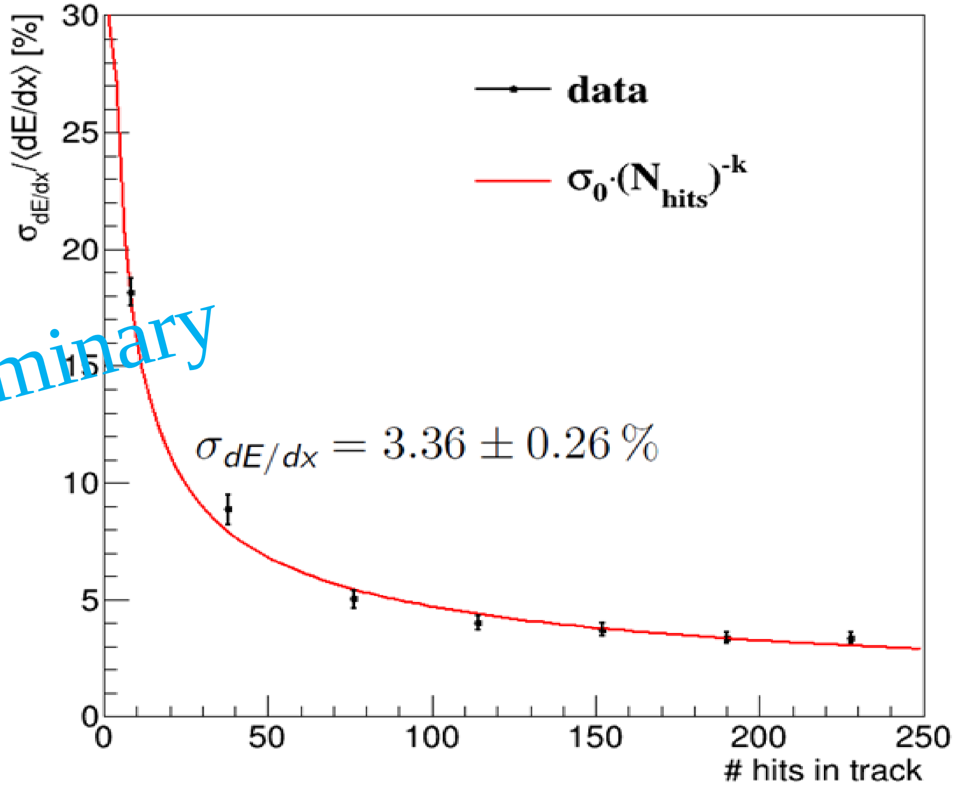


Reconstruction events and ^{55}Fe X-ray spectrum profile(middle) and cosmic ray spectrum(Right)

Pad TPC prototype with 266nm UV laser tracks

- The TPC prototype integrated 266nm UV laser tracks has successfully developed.
- Analysis of UV laser signal, the spatial resolution, dE/dx resolution
  - Spatial resolution can be less than **100 μm along the drift length** of 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%

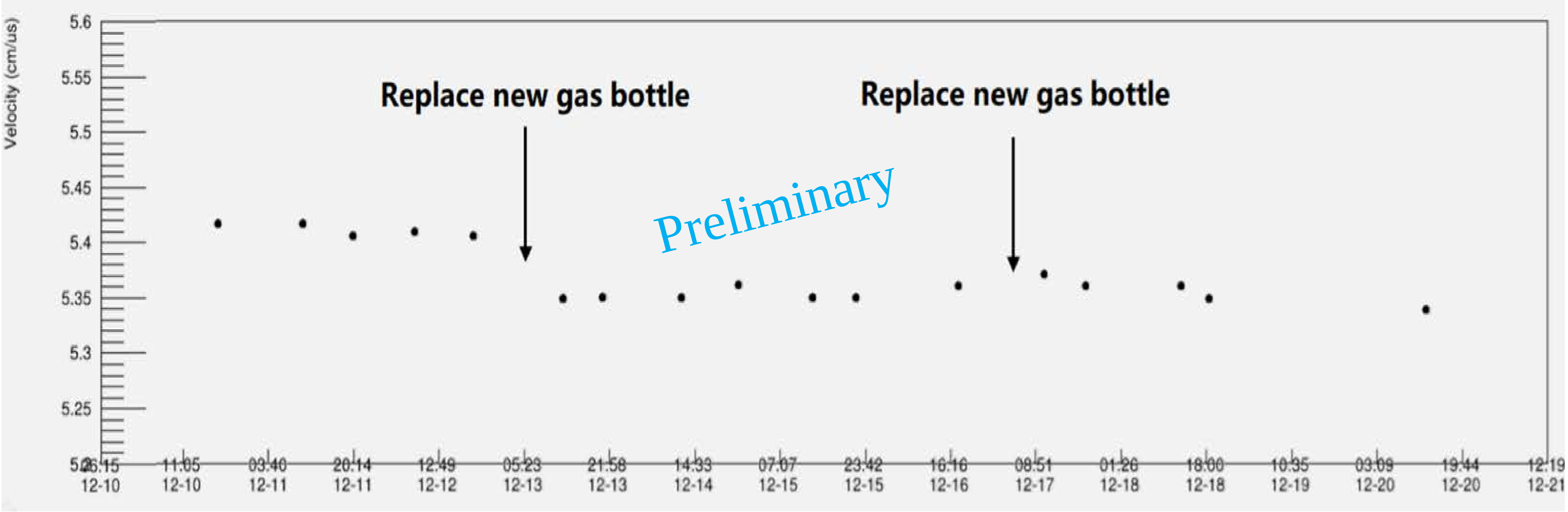




https://doi.org/10.1016/j.nima.2022.167241

Monitor the drift velocity using UV laser

- TPC prototype can monitor the drift velocity using UV laser tracks in two weeks
- Operation mixture gases is T2K gas in the TPC prototype chamber
- Recorded and compared the drift velocity and temperature
- The **sensitive of the electron drift velocity can be monitored using the UV laser tracks**

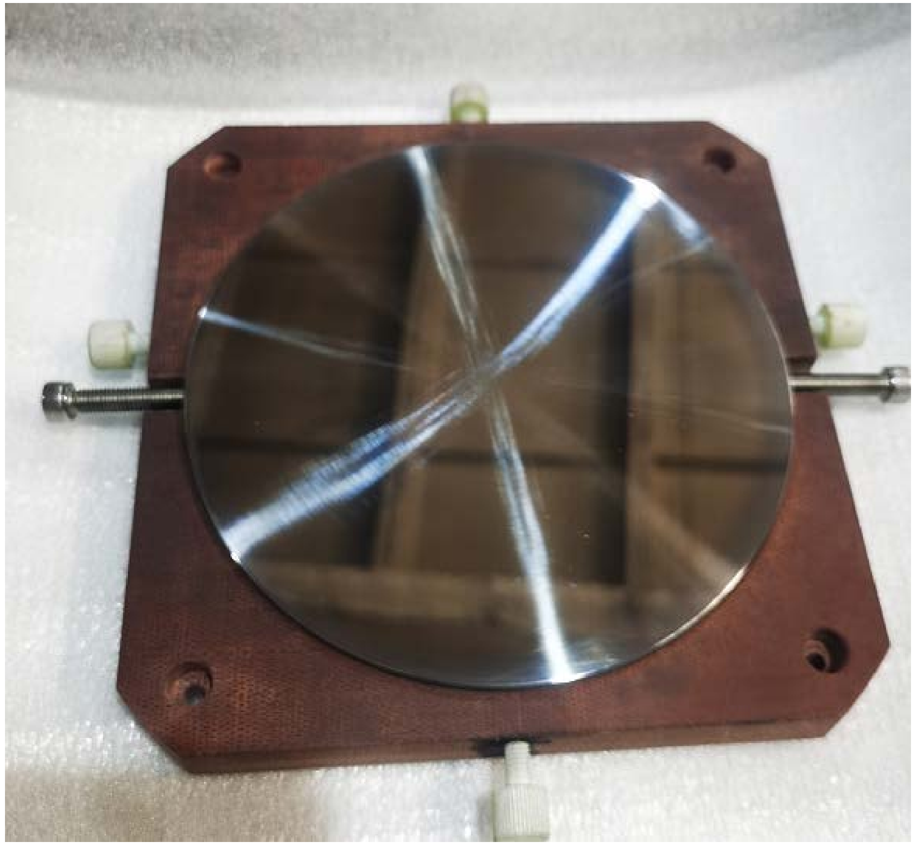


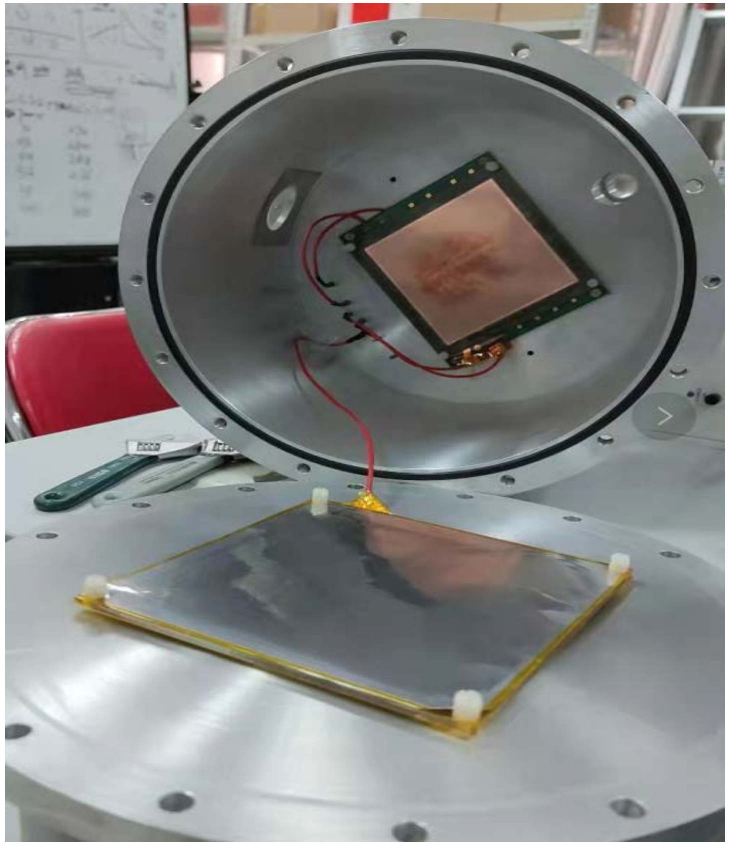
- UV light create the massive primary electrons in chamber

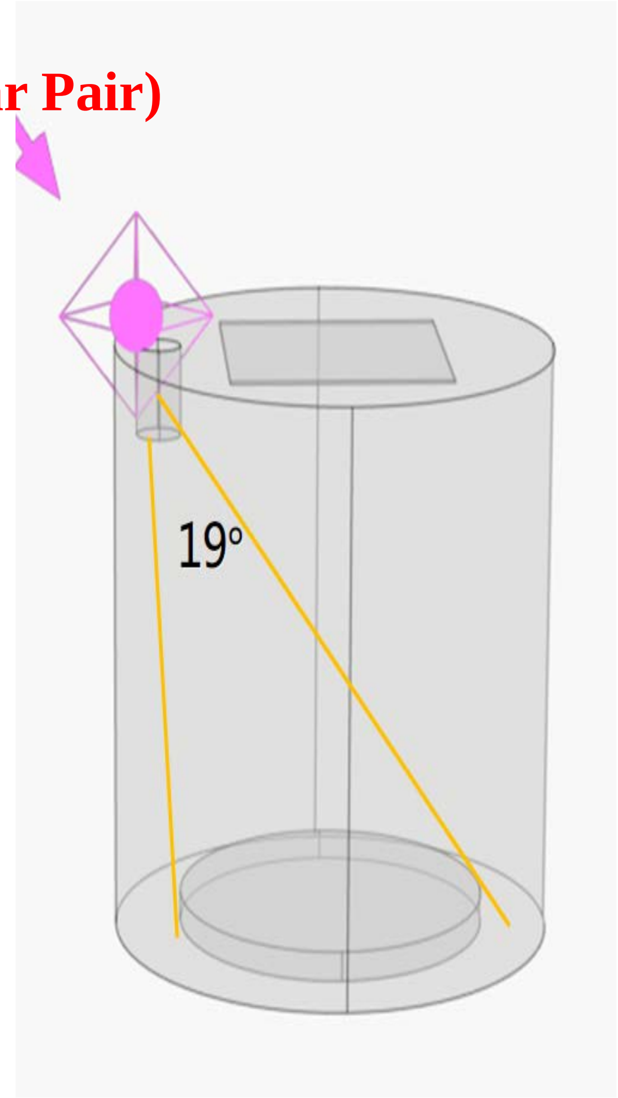
Testing the UV light created the massive electrons by photoelectric effect

UV light created the massive primary electrons

- Ions will fill in the drift chamber of TPC to mimic the ions distortion
- **Metal mesh polished Aluminum**: 600/800/1000/1200/1400/2000 (**LPI: Linear Pair)**
- Experimental testing of the current at record detector layers

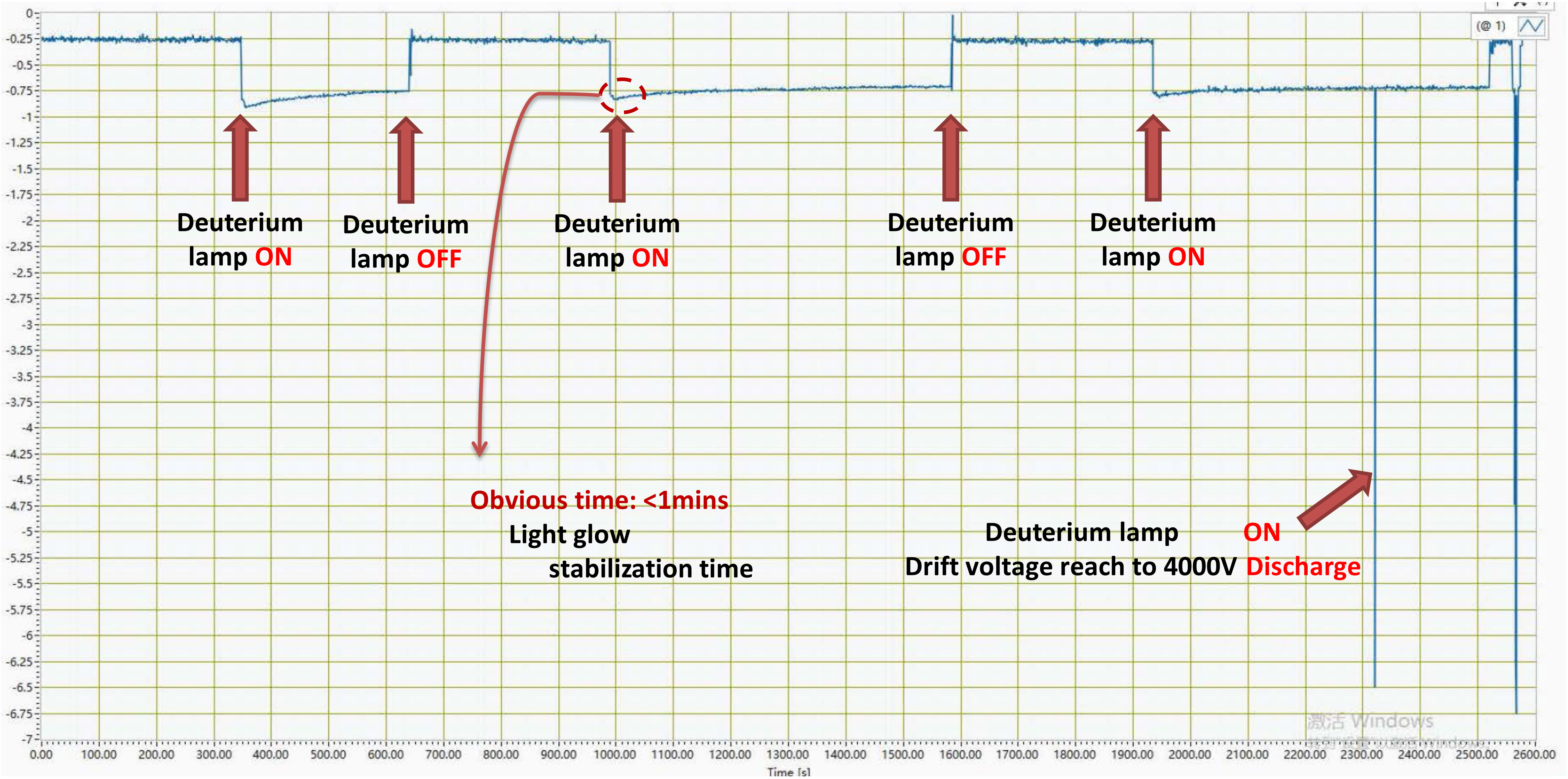






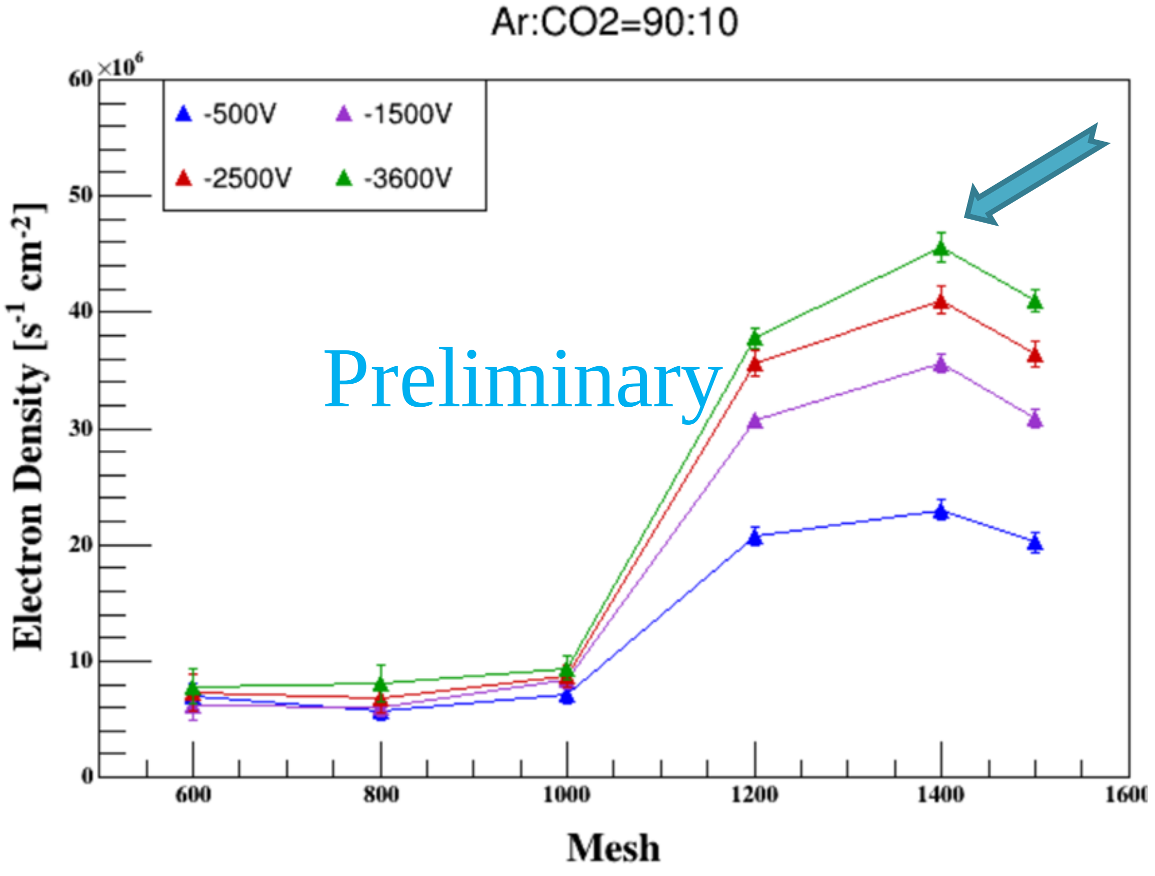
Testing the UV light created the massive electrons by photoelectric effect

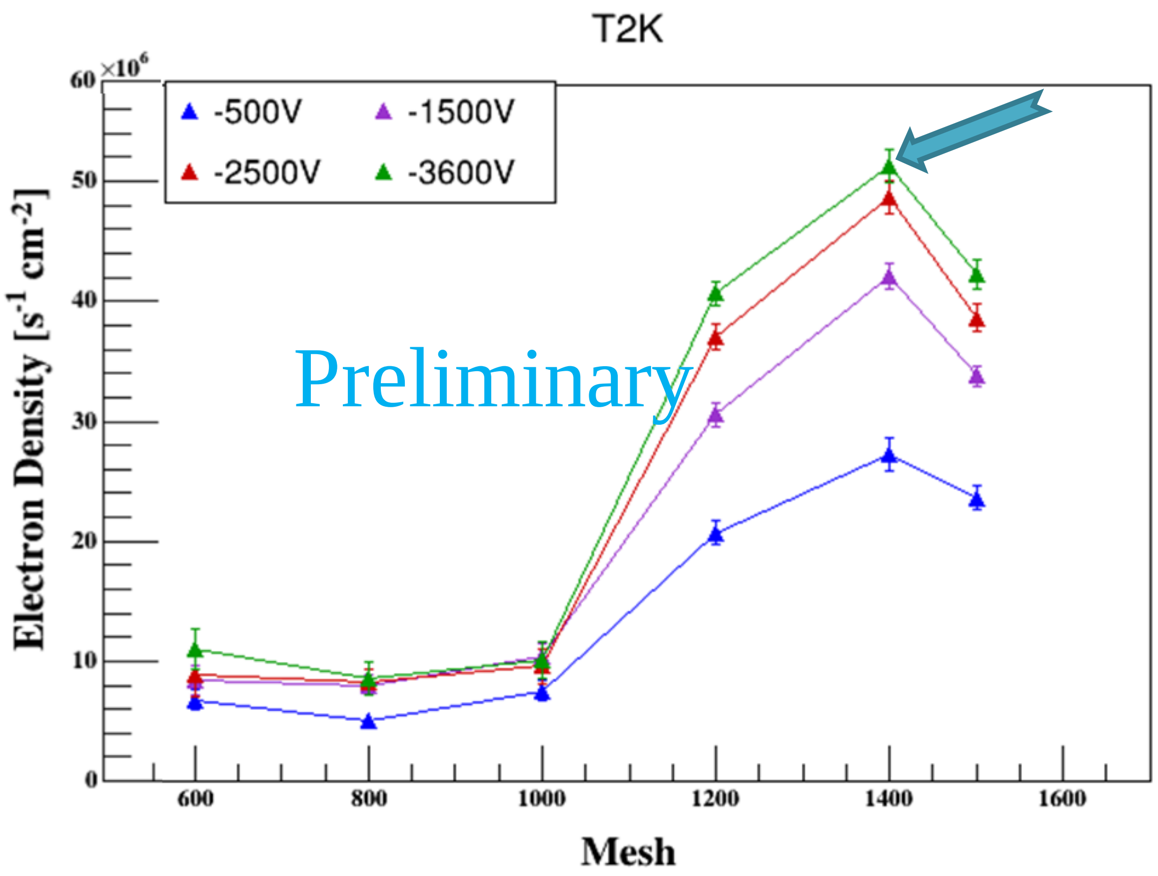
- Results of the experimental studies **: very good stable** current obtained



Testing the UV light created the massive electrons by photoelectric effect

- The different LPI Aluminum's surface tested the stable current
- The maximum current reached at 1400LPI Aluminum's surface (**Very stable**)
- Detector has been studied under the two different mixture gases
  - Very similar trends **from 30V/cm to 210V/cm (Electric field of drift)**
- The novel method **can meet to study the deviation of the track** using the prototype



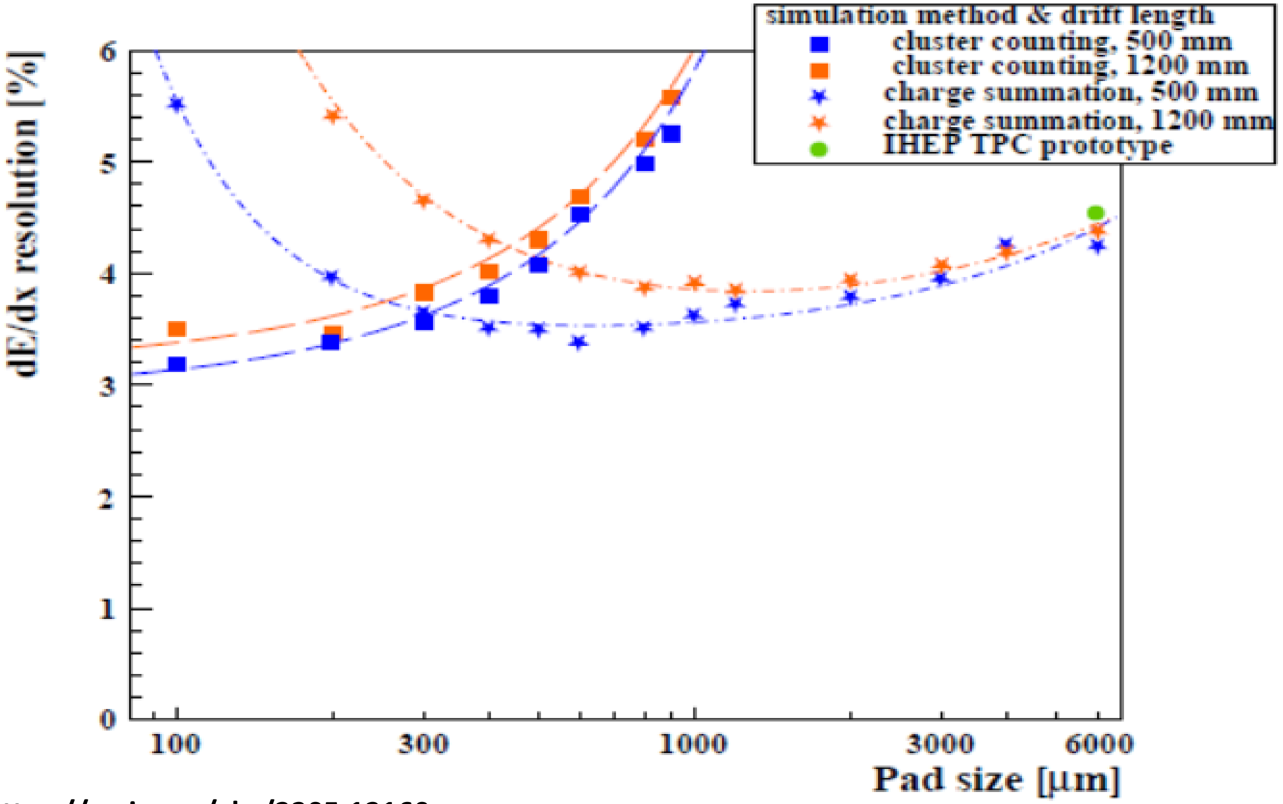


- Towards pixelated readout TPC technology

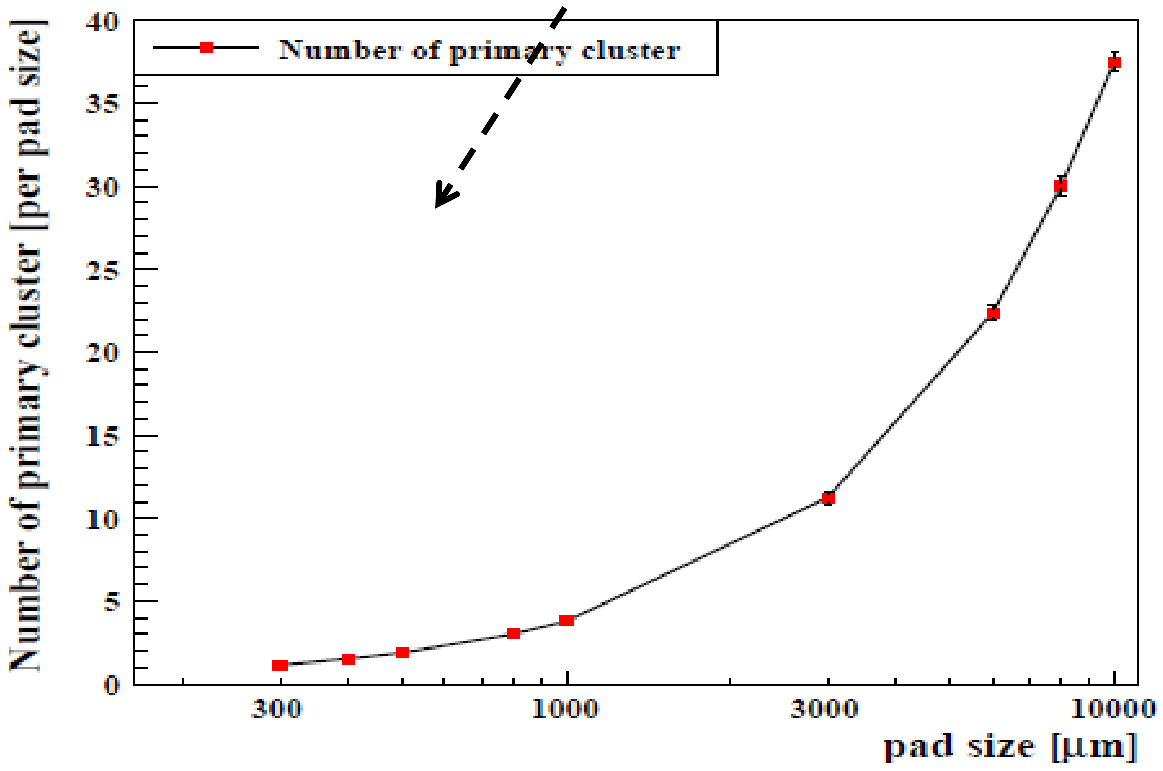
High granularity for improved PID in TPC

- Current full ILD reconstruction: 6mm pads → **~4.8% dE/dx resolution**
- 6mm → 1mm: 15% improved resolution via the charge summation (dE/dx)
- 6mm → 0.1mm: 30% improved resolution via the cluster counting (dN/dx)
  - 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

All studies ongoing



Simulation of the primary cluster along the drift length

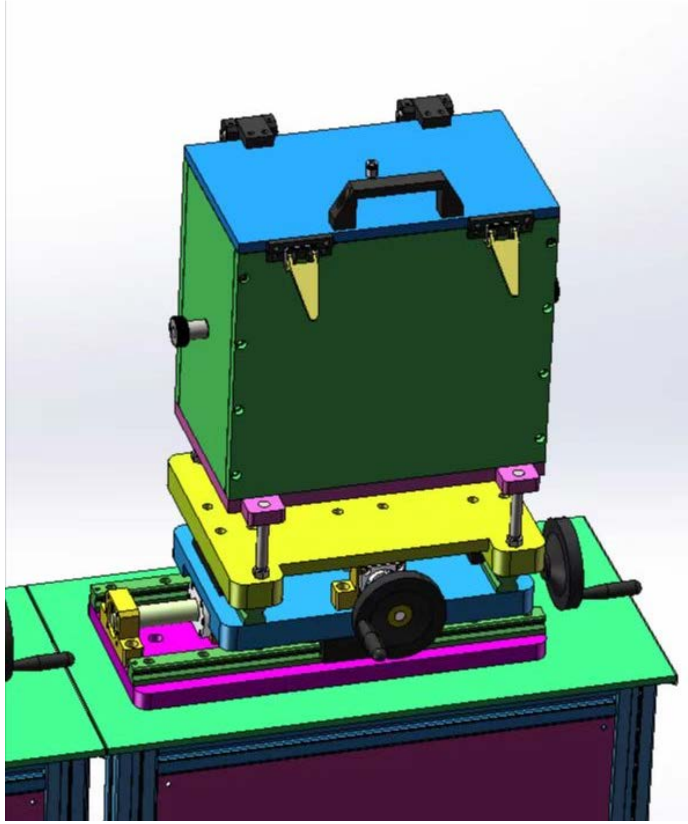


https://arxiv.org/abs/2205.12160

Current R&D effort: New TPC prototype design and plan at IHEP

- Study some new parameters complemented previous circular TPC
- Cascaded TPC detectors to test dE/dx and IBF distortion integrated with UV light
- New FEE ASIC chip wafer R&D: **500um×500um pixelated readout based**
- Plan： new TPC detector prototype can meet to experimental study **under 1.0T beam test**

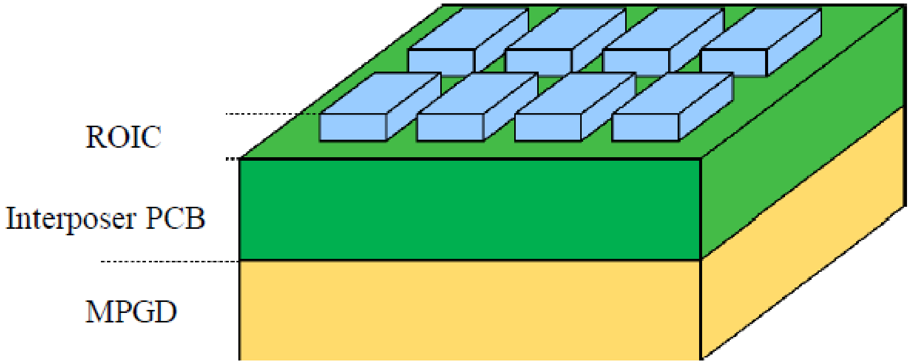
Grid TPC progress:
See Peter 's talk today



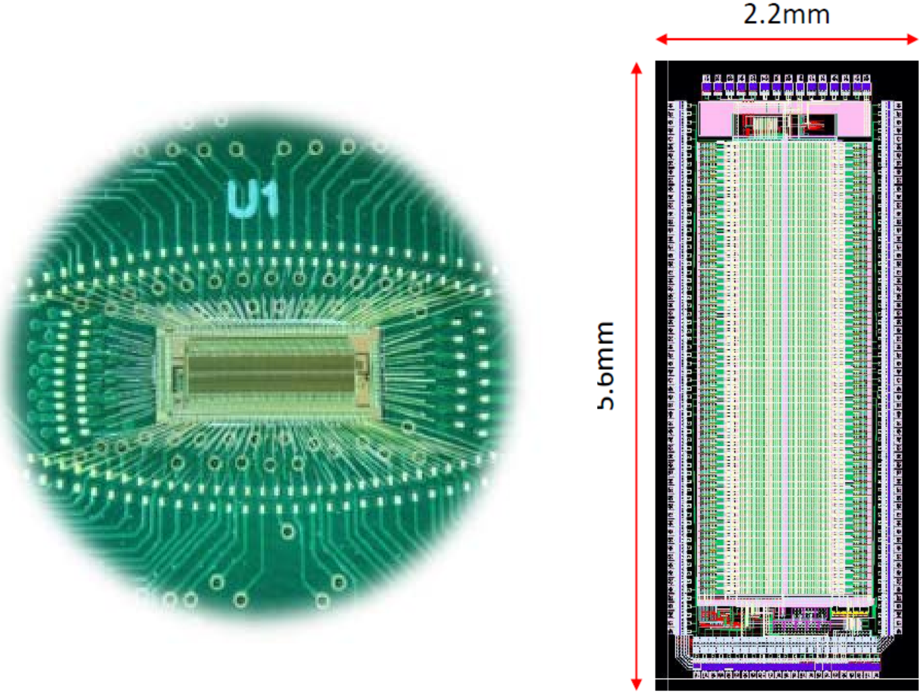
Bump bond pixelated readout with Micromegas detector	Module size	To be addressed by R&D
• **≥300 μm×300 μm** • Developed the readout chip by Tsinghua • Developed the Micromegas detector sensor at IHEP • Development of the new module and prototype	1-2 cm^2	• Research on pixelated readout technology realization • Optimization of cluster profile and pad size • Study of the 'dN_{cl}+dx'
	100 cm^2	• Study the distortion using UV laser tracks and UV lamp to create ions disk • In-situ calibration with UV Laser system • Study of the '$dE/dx+dN_{cl}/dx$'

Current R&D effort: Pixelated TPC R&D for 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, TPC detector prototype using the pad with integrated 266nm UV laser tracks have been developed for the future e+e- colliders.**
- **The detector module will assembled and commissioned with the low power consumption ASIC chip. Some update results of TPC module have been studies, it can effectively reduce ions at the low gain without the space charge and the discharge.**
- **Some update results of TPC prototype have been studies, the prototype is working well, and the results indicated that 266nm UV laser beams will be very useful. UV light can created the enough massive primary electrons in the chamber.**
- **Synergies with CEPC/LCTPC/FCCee/EIC allow us to continue R&D and ongoing, we learn from all of their experiences.**

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Many thanks!