Drift Chambers: Applications in BESIII and R&D for Future High-Energy Physics Experiments

Institute of High Energy Physics, CAS

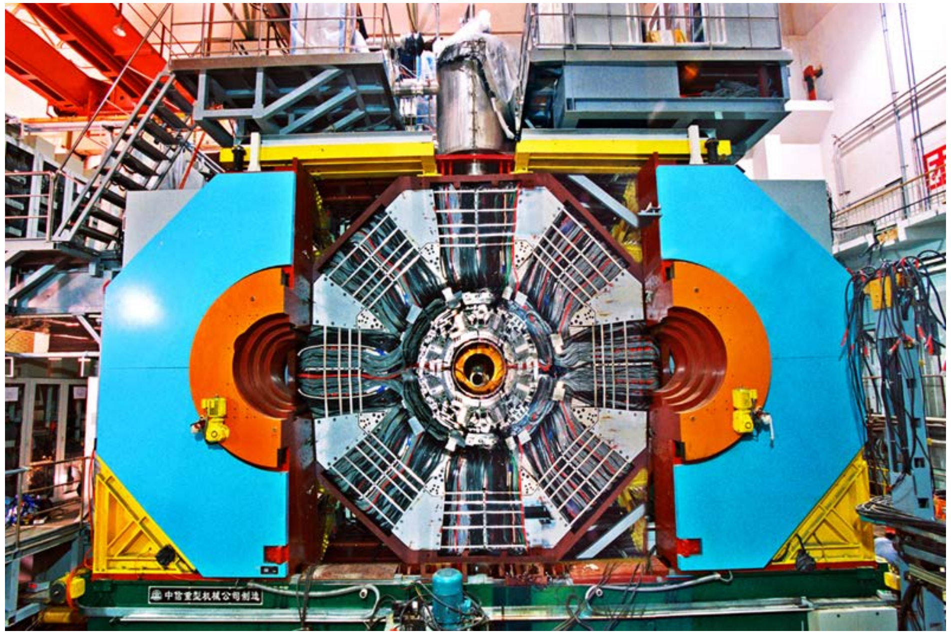
Mingyi Dong

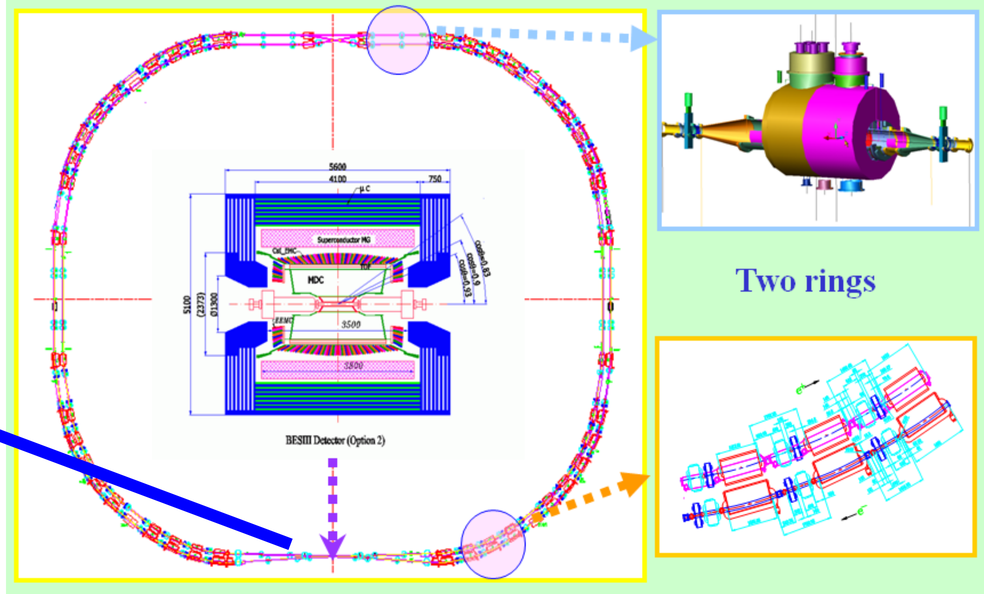
Outline

- **BESIII drift chamber (MDC)**
- **MDC aging study**
- **R&D for Future High-Energy Physics Experiments**
- **Summary**

The BESIII experiment

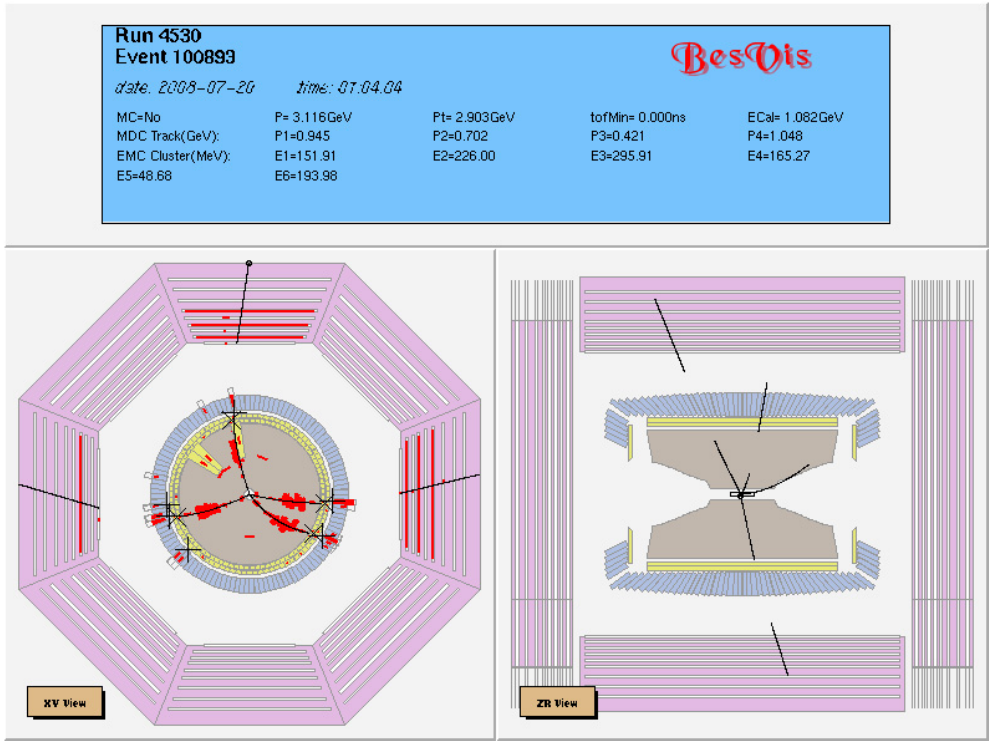
- Beijing Spectrometer(BESIII) is a general purpose detector at Beijing Electron-positron Collider (BEPCII), $E_{cm} \approx$ 2-5 GeV, $L_{peak} \approx 10^{33}/cm^2/s$
- Versatile researches in τ-charm physics
- BESIII collaboration has >700 members from 93 institutes in 15 countries and regions

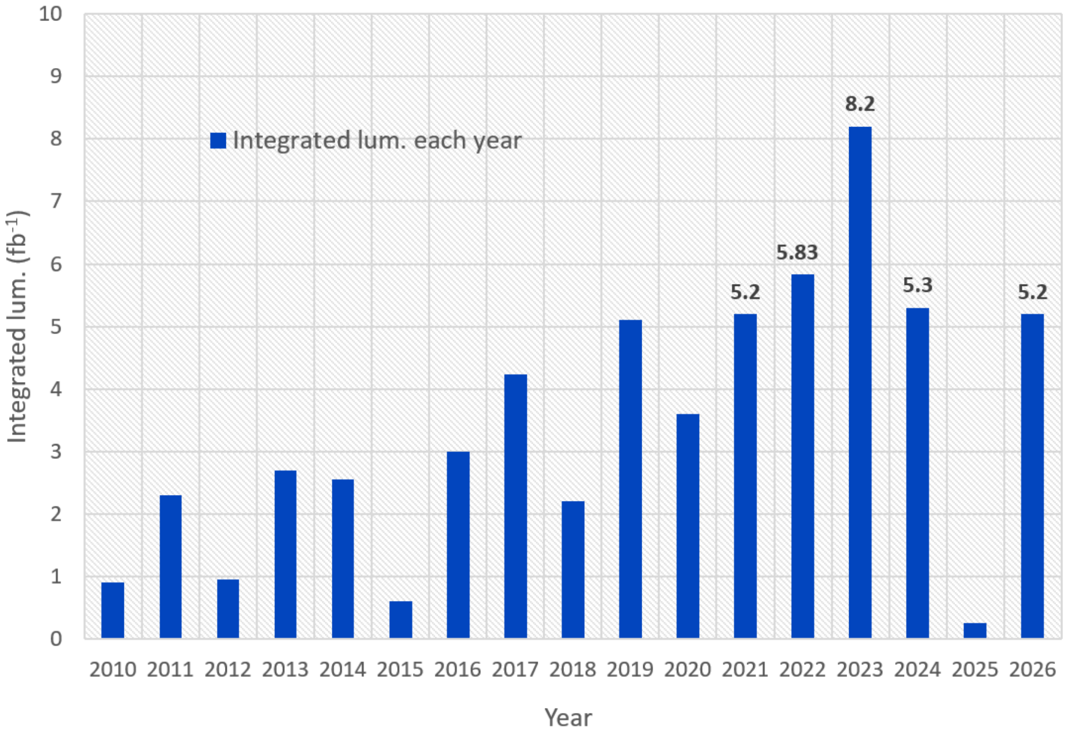




The BESIII experiment

- Started commissioning run in July, 2008
- Started data collection in 2009
- More than 17 years operation
- BEPC and inner tracker of BESIII were upgraded in 2024-2025, and BESIII will continue to operate until 2035



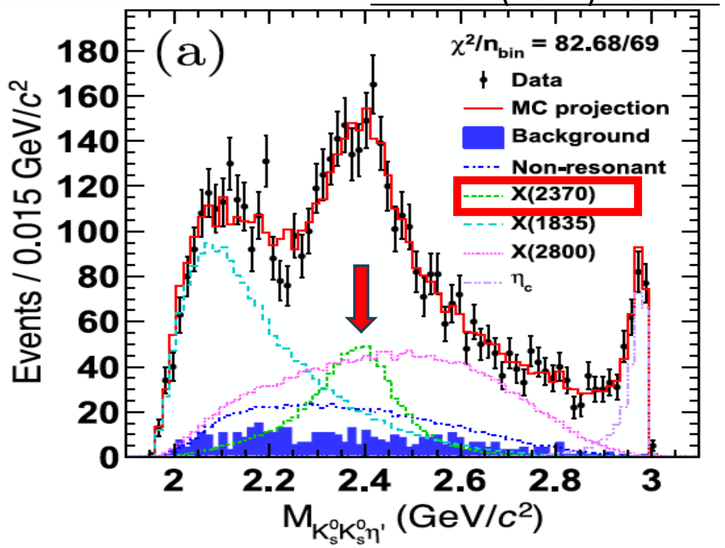


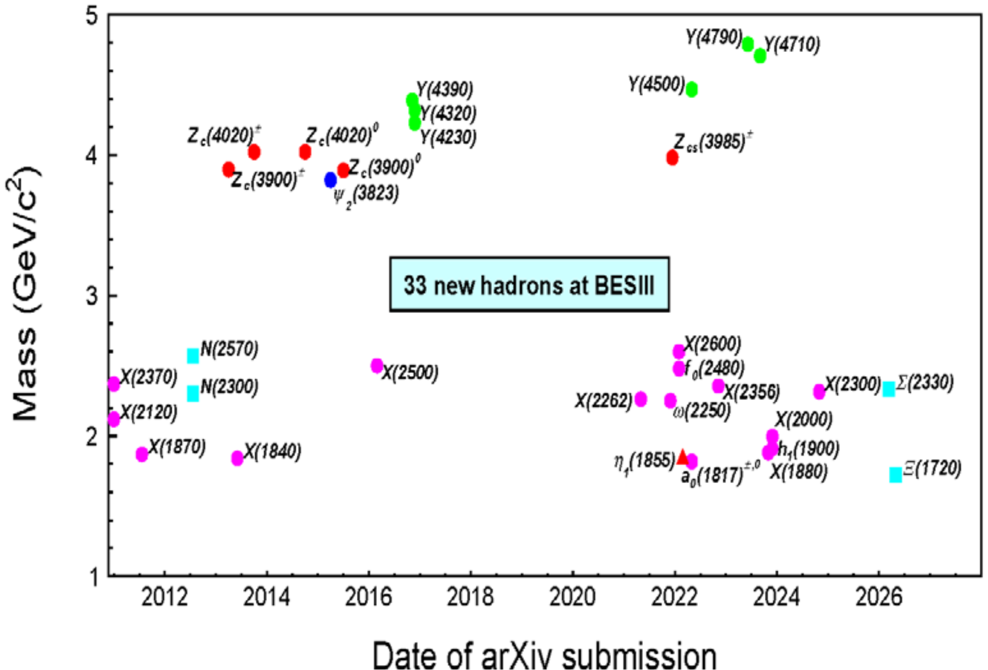
- Total integrated lum. : 58.2 fb^{-1}
  - 10 B J/ψ events
  - 4 B ψ(2S)events
  - 20 fb^{-1} ψ(3770)
  - 3.2 fb^{-1} Ds
  - 27.1 fb^{-1} E_{cm} > 4GeV data
  - ……
- Most of them are the largest events in the world

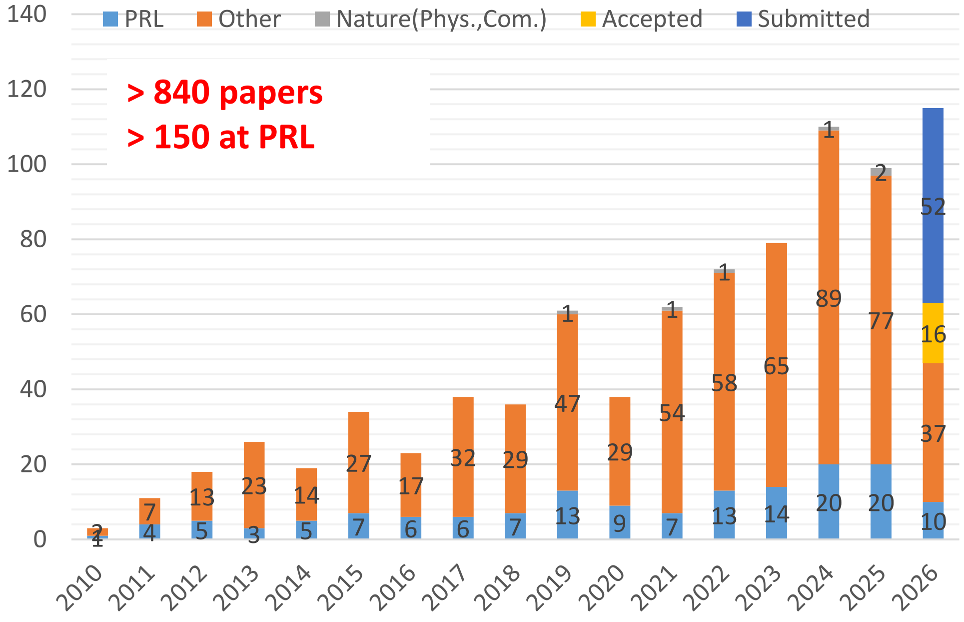
Physics studies

- A series of new particles have been discovered, especially novel hadrons including the glueball candidate X(2370), hybrid states, multiquark states, and so on.
- A suite of precision measurements have been accomplished, such as determinations of decay constants and CKM matrix elements, studies of charmed baryons, searches for CP violation, etc.

PRL 132 (2024) 181901

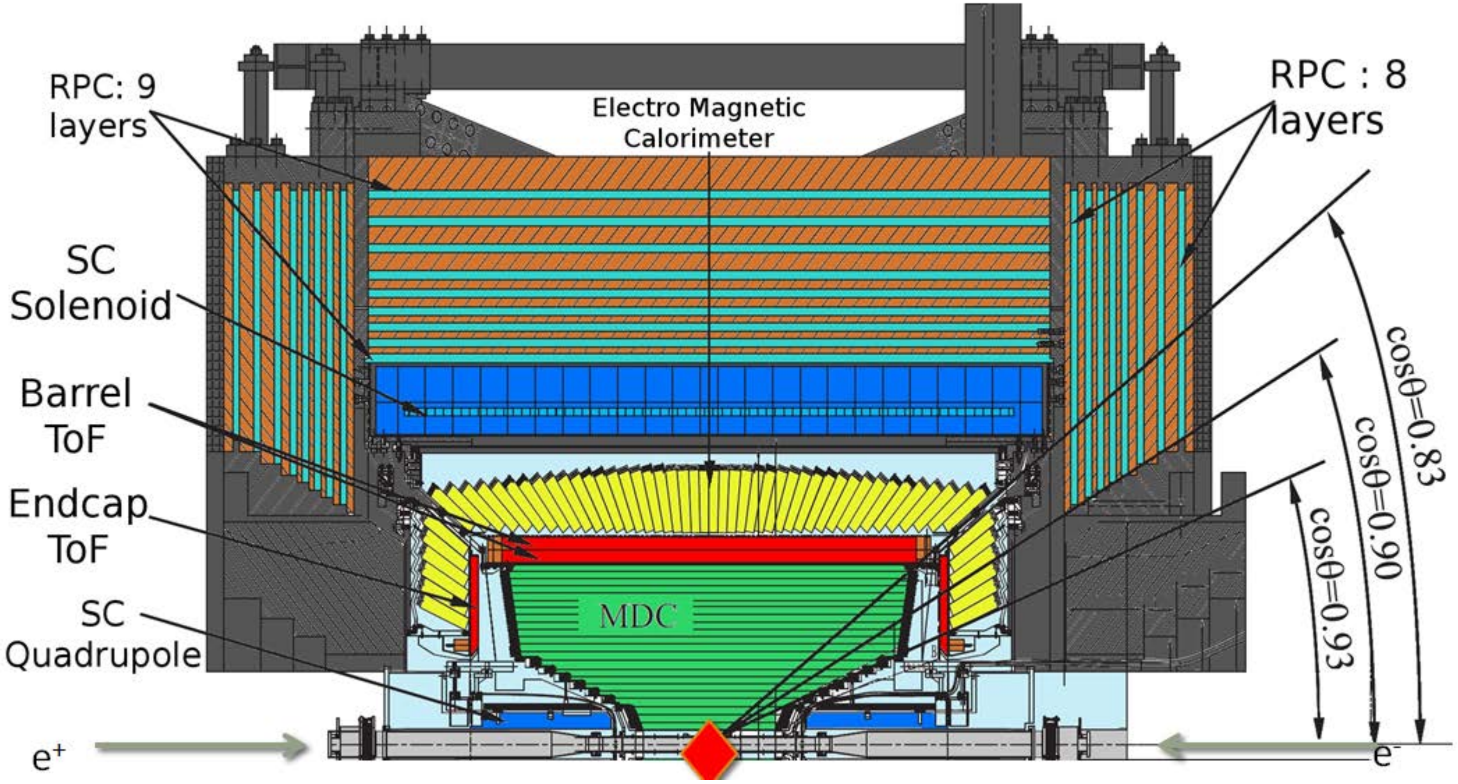




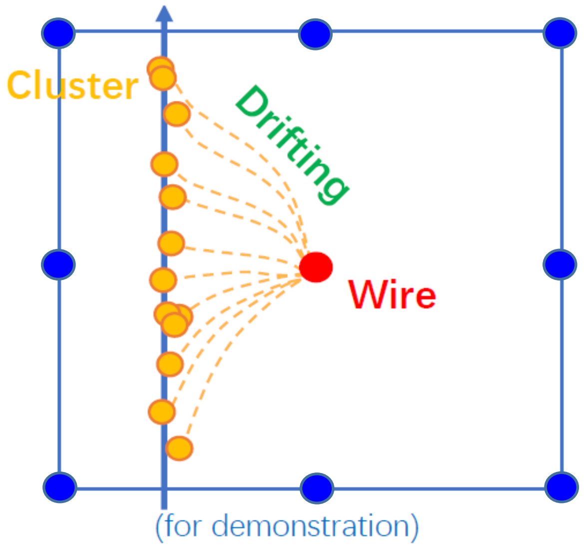


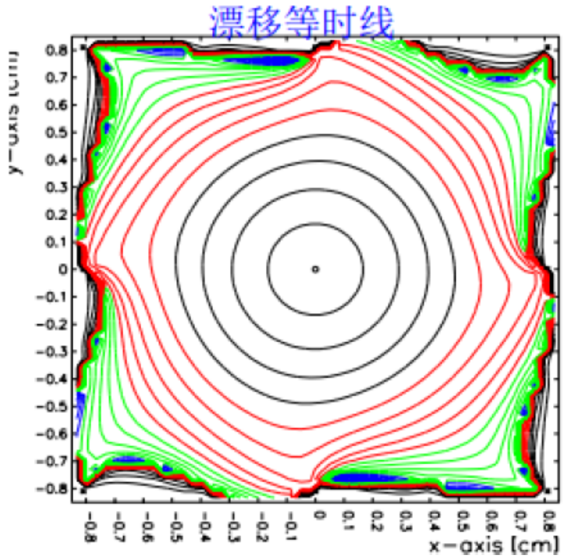
BESIII detector

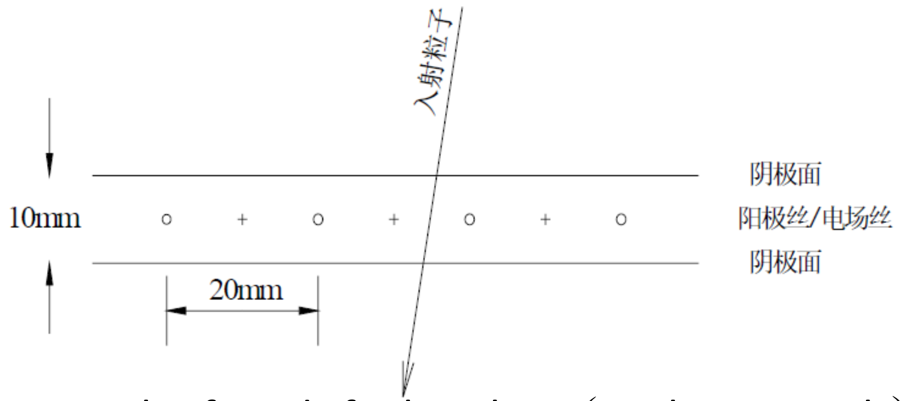
- He-based gas drift chamber with single-wire resolution < 130 μm
- CsI (Tl) crystal electromagnetic calorimeter with energy resolution < 2.5% at 1 GeV
- Time of Flight (TOF) with time resolution <100 ps
- Superconducting solenoid magnet with a magnetic field of 1 T
- RPC-based muon detector



Drift chamber







The first drift chamber（Walenta, et al.）

Charged particles collide with drift chamber gas atoms to produce excitation or ionization, losing energy and creating ionization electrons along tracks.

- The electrons drift to anode wires under the electric field, forming an electron avalanche near the wires to generate readout signals.
- Particle positions are reconstructed from electron drift times via the X-T relation
- Signal charge encodes the energy loss of incoming particles

$$\sigma_x = \frac{1}{\sqrt{n}}\sqrt{2Dt} = \frac{1}{\sqrt{n}}\sqrt{\frac{2DL}{W}} = \frac{1}{\sqrt{n}}\sqrt{\frac{2DL}{\mu E}}$$

$$\sigma^2 = \sigma_{diffusion}^2 + \sigma_{ionization}^2 + \sigma_{electrinics}^2$$

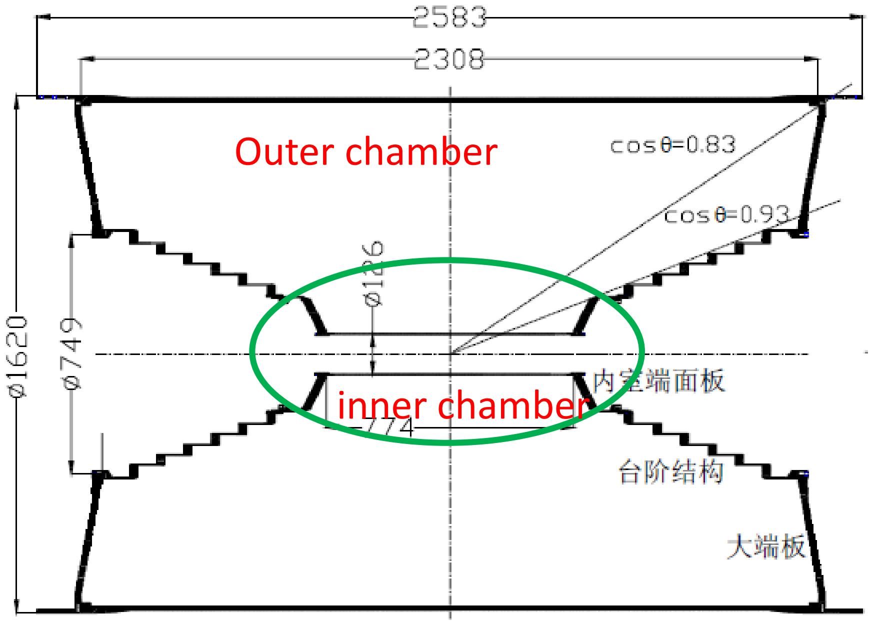
BESIII Main drift chamber (MDC)

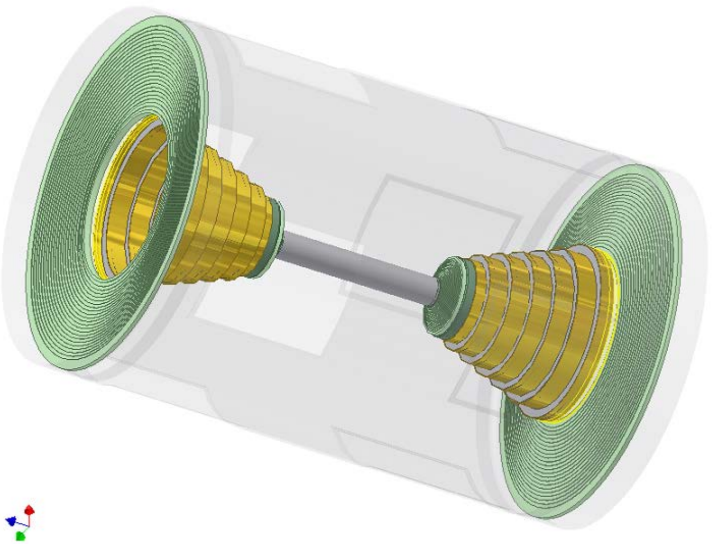
- Main tracking detector for the charged particles

  Position, momentum and dE/dx measurements

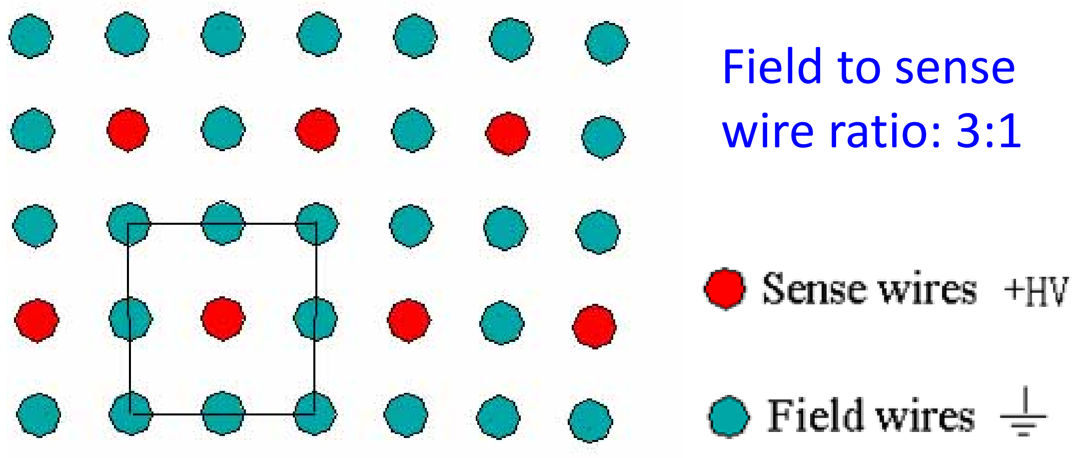
- Consists of inner chamber and outer chamber

Parameters	Specification
Number of layer	43 (inner chamber: 8 layers+ outer chamber: 35 layers) 19 axis layers， 24 stereo layers
Number of cell	6796
R extension	63 mm → 810 mm
Length	2308 mm
Inner cylinder	1.2mm- thick CF
Outer cylinder	11.5mm- thick CF
End plates	18mm-thick Al （6 stepped parts， inner end plate）





Small cell design



Field to sense wire ratio: 3:1

- cell size：
  inner chamber: 12mm×12mm
  outer chamber: 16.2mm×16.2mm

- Sense wires: ϕ25μm W (Au)
- field wires: ϕ110μm Al (Au)
- 28680 wires in total

Attractive features of small cells

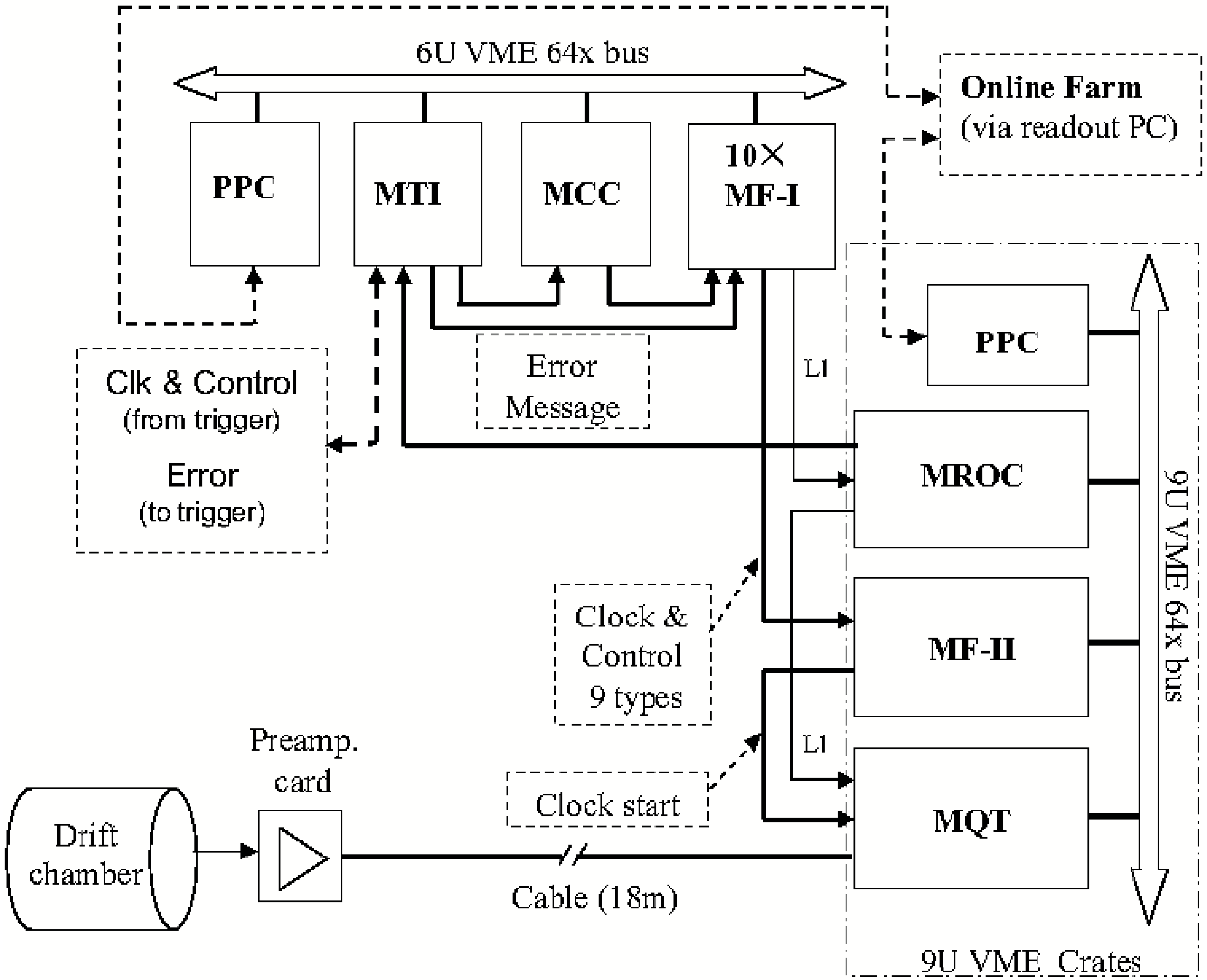
- Small drift distance → fast trigger
- Can reduce electron diffusion → improve spatial resolution
- Can put more layers in limited space → improve $\sigma_{dE/dx}$
- Reduce accumulated charge of the cells → slow down aging

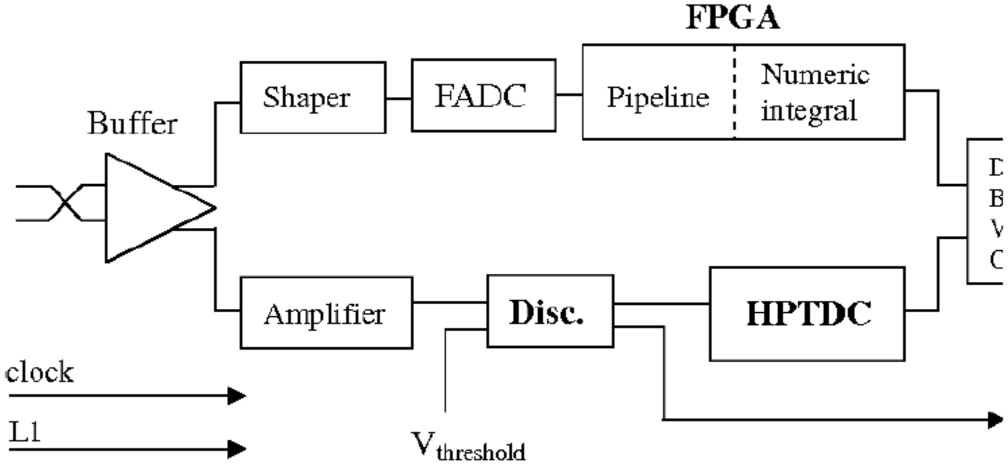
He based gas mixture

- **Gas**
  - He based gas mixture , He : C_3H_8 = 60％ : 40％
  - low material budget to reduce multiple scattering
  - X_0: 500 m, v_e=3.8 cm/μs

- **High Voltage**
  - About 2200 V, same for the cells in same layer, little difference between each layer
  - Set HV of the first four layers to 98%, 98.5%, 99%, and 99.5% of the nominal value, respectively, due to high beam induced background
  - Gas gain： ~ 2×10^4 @2200V

Readout electronics

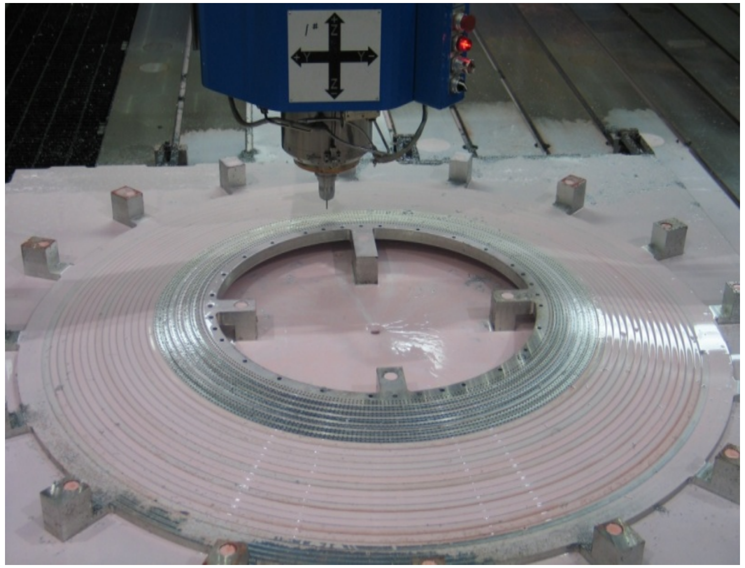




T and Q measurement

Construction of MDC: Large endplates

- The First Domestic Large-Scale High-Precision Multi-Hole Endplate with a diameter of 1.6 m.
- Each plate contains 21,152 wire holes with a diameter of 3.2 mm. The positional precision for all holes is of ±25 μm.
- Two large end plate and 14 stepped plates, together with 14 stepped connecting rings and inner/outer cylinder, are aligned and assembled to form a left-right symmetric drift chamber.
- Assembly precision: single-end X/Y deviation < 50 μm, and corresponding X/Y deviation between two ends < 100 μm.

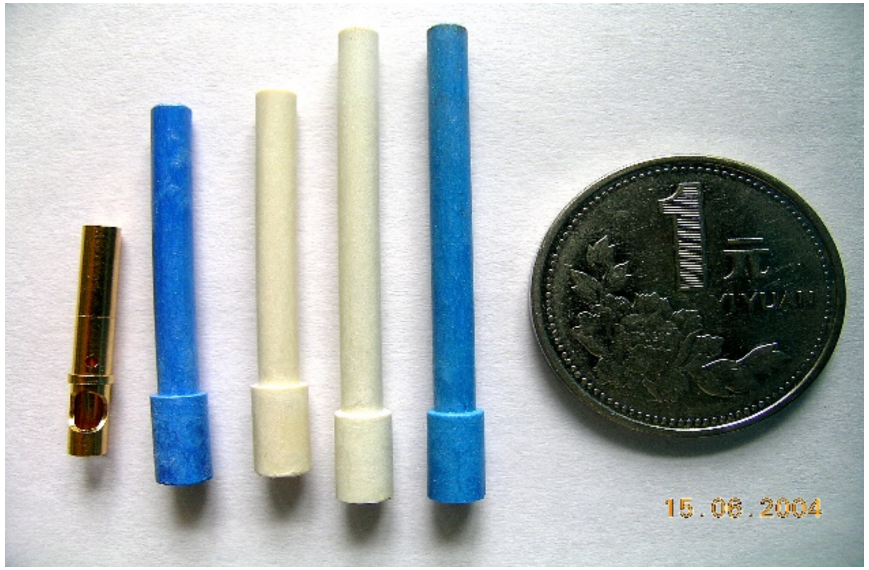


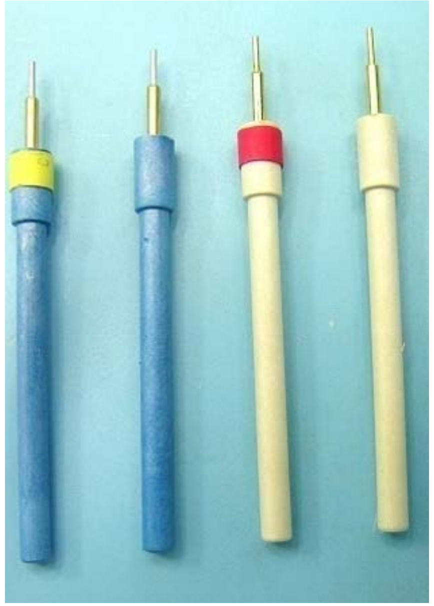
Construction of MDC: Inner and outer cylinder

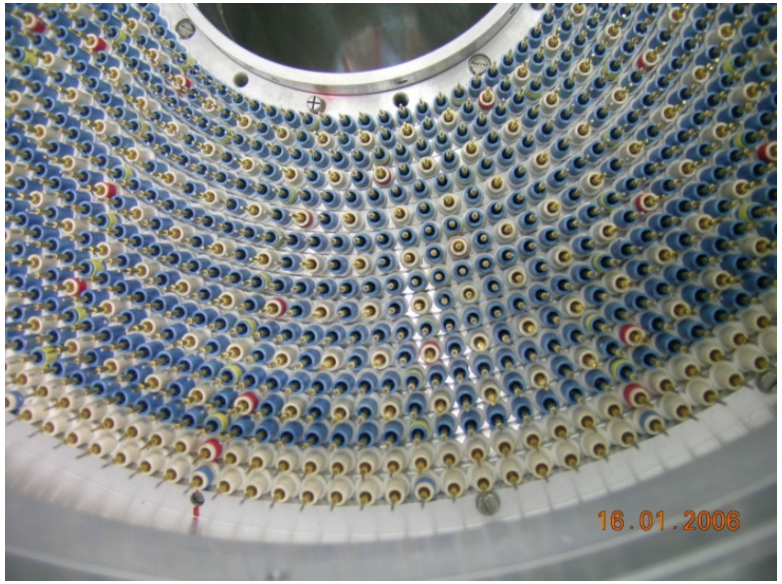
- Large Carbon-Fiber Inner and Outer Barrels
- Outer CF cylinder diameter: 1.6 m, length: 2.5 m. It can withstand an axial load of 5 tons with deformation limited to < 50 μm.
- Eight observation windows are machined on the outer barrel, which was sealed after wire stringing.
- The CF cylinders are joined to the end positioning rings at both ends to guarantee structural strength and gas tightness.

Construction of MDC: Feedthrough

- Feedthrough is key component for wire fixation and precise positioning.
- Each unit consists of a small clamping tube for wire fixing, a large copper tubes for electrical conduction, and an insulating part.
- The clamping tube features an inner diameter of 180 µm.
- The outer insulator withstands a high voltage of 4000 V,
- The assembly maintains a concentricity tolerance of 50 µm.

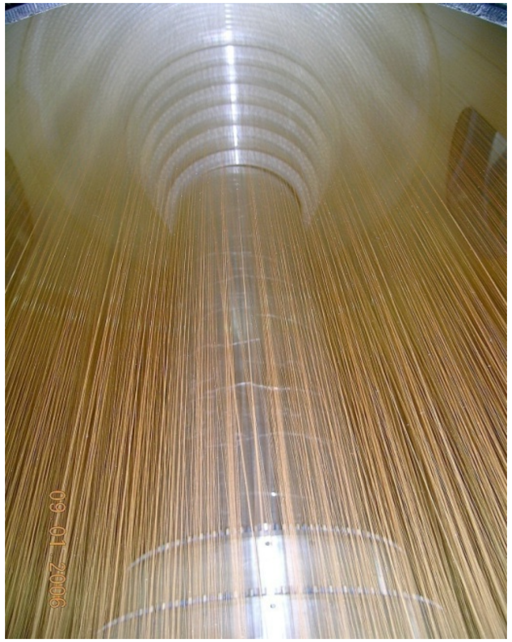




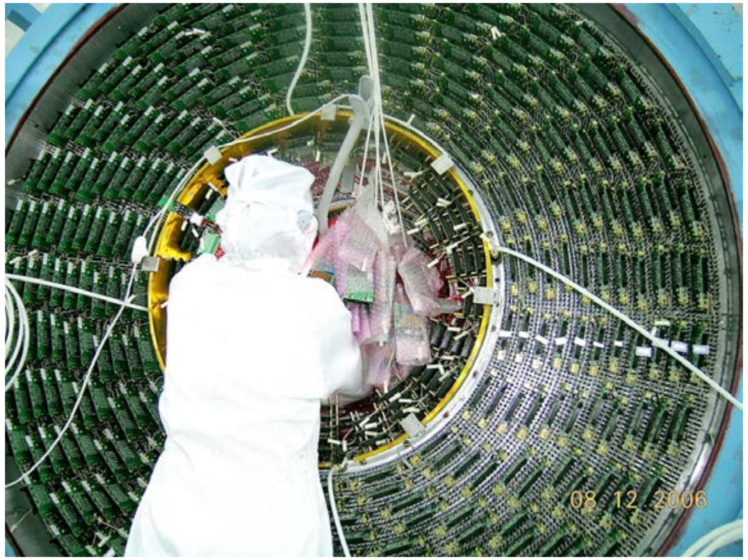


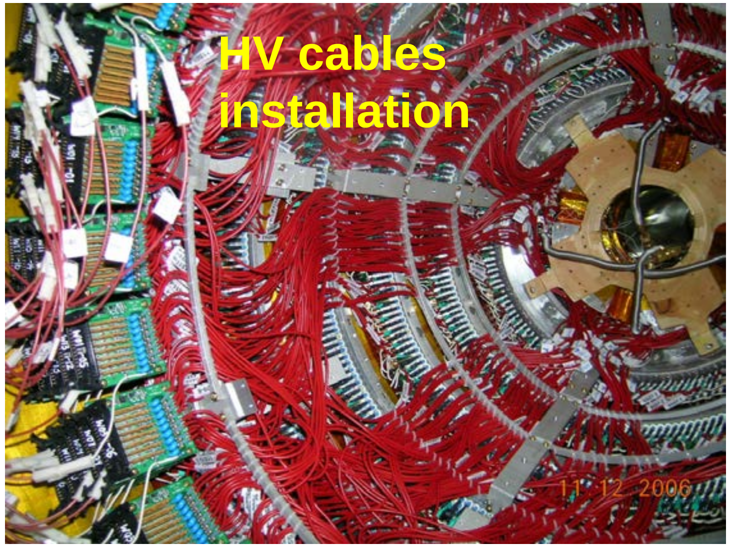
Construction of MDC: Wiring

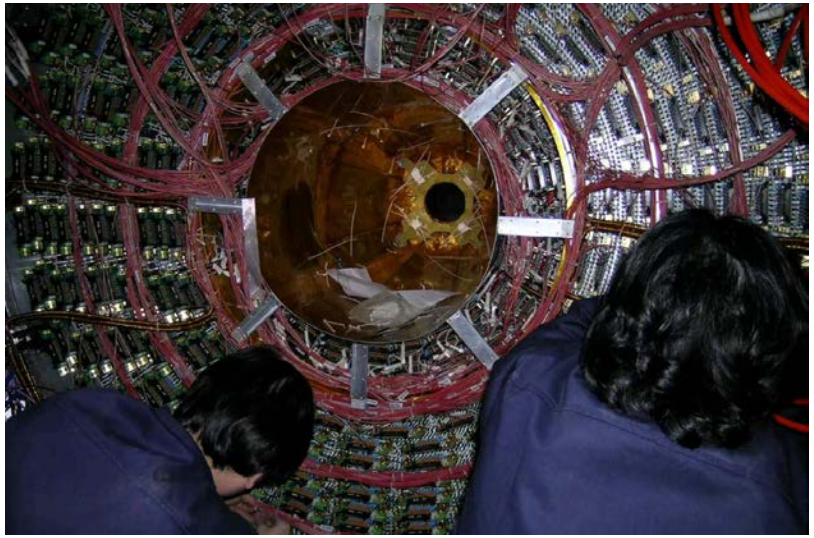
- A dedicated wiring machine was developed to support the drift chamber and enable vertical wire stringing.
- The geometric alignment error of the wiring machine is less than 12 μm, and the maximum error of horizontal rotation precision is 8 μm.
- Prestress is applied to endplates to generate pre-deformation matching the deformation of endplates after full wire stringing. Prestress rods are removed gradually during wiring to stabilize the tension of installed wires.
- Vertical wiring technology includes wire threading, tension loading and wire clamping.
- Over 18 years of operation, no loose or broken wires have occurred.

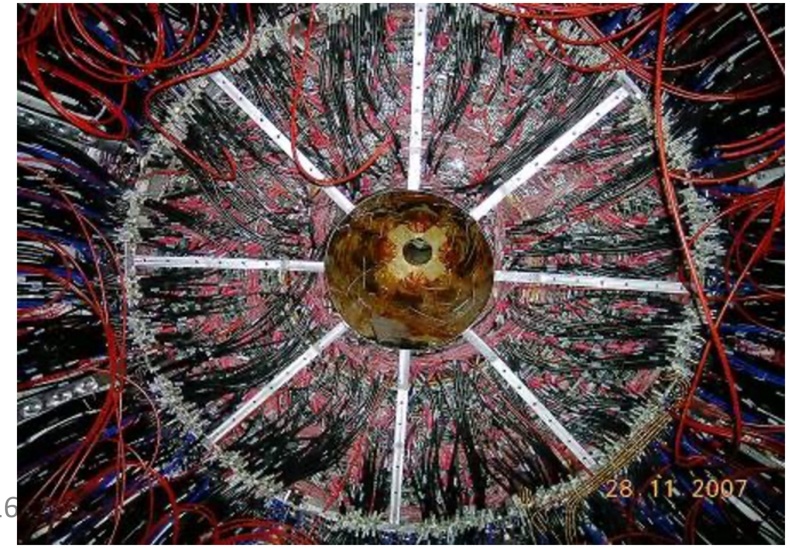


Construction of MDC





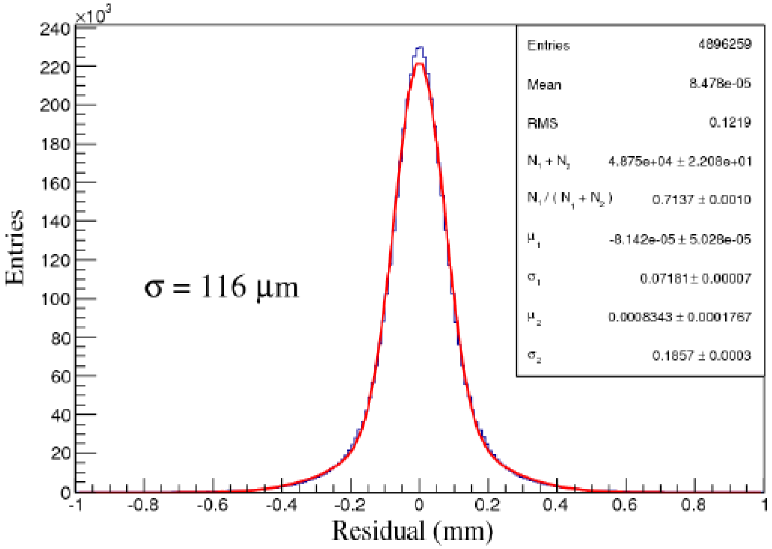




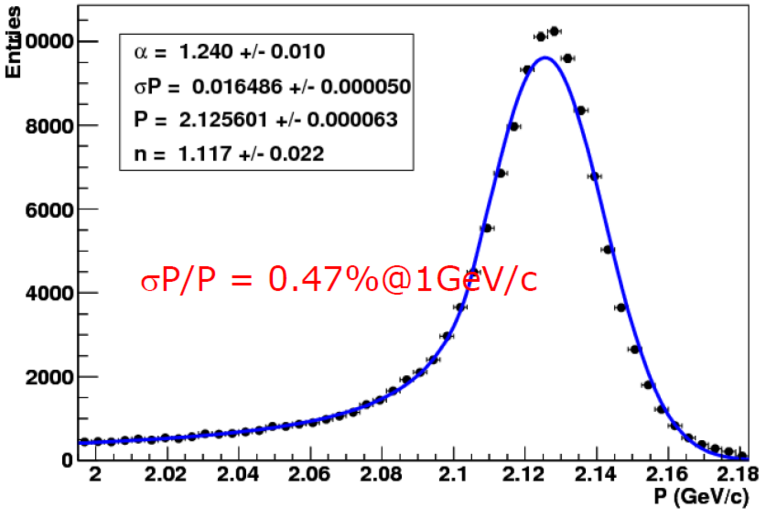
Performance of MDC

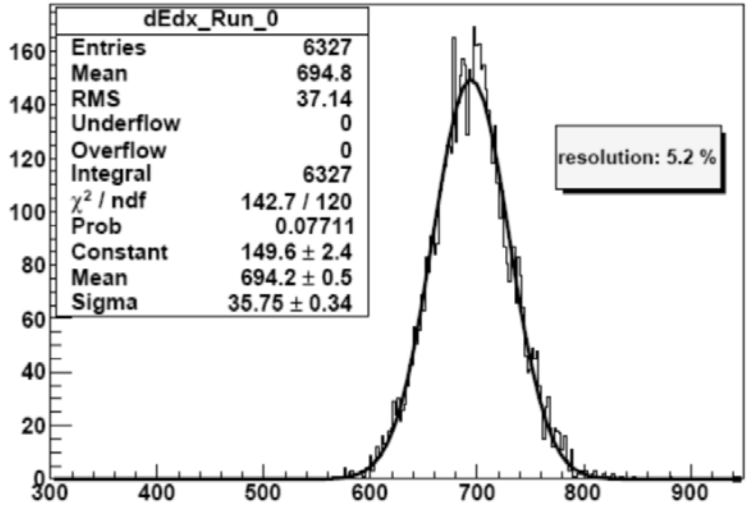
Parameters	Design Performance	Achieved Performance
$\sigma_{r\phi}$	$130\ \mu m$	$\sigma_{r\phi} = 115\ \mu m$
$\Delta p/p$	$0.5\%@1GeV$ (B=1T)	$0.47\%@1GeV$ (B=1T)
$\sigma_{dE/dx}$	6%	5.2%

Residual distribution



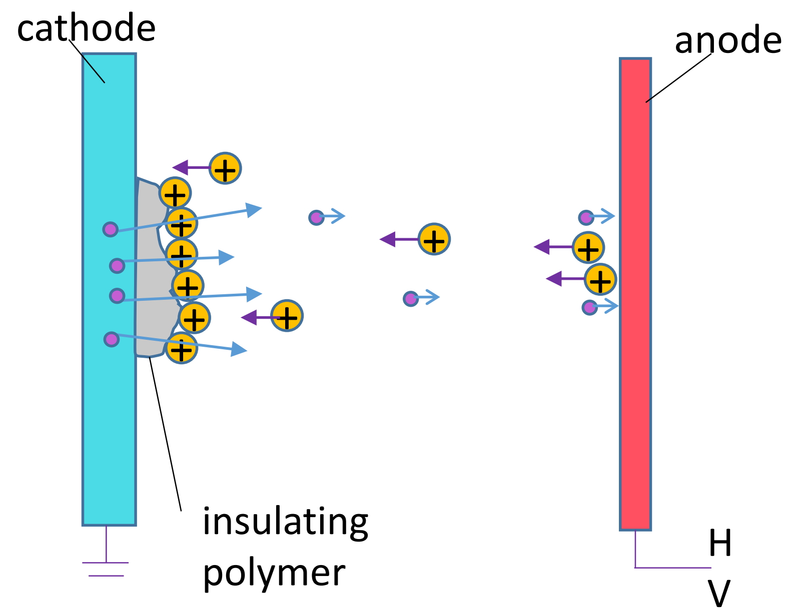
Bhabha from Run 50500



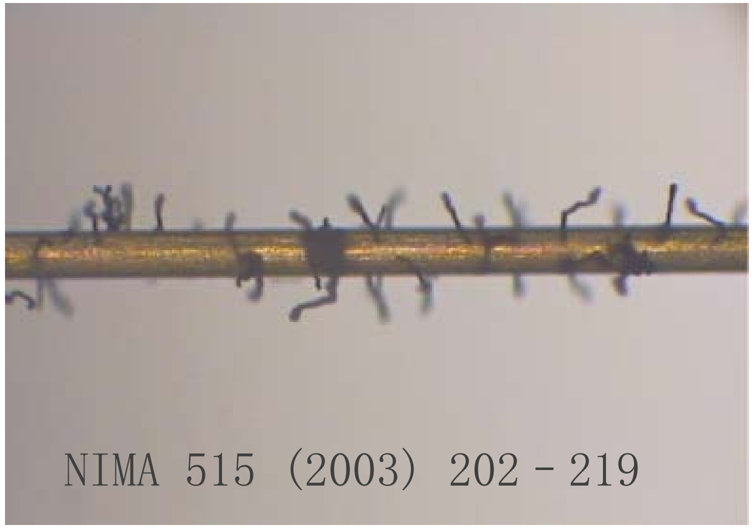


Aging phenomenon in MDC

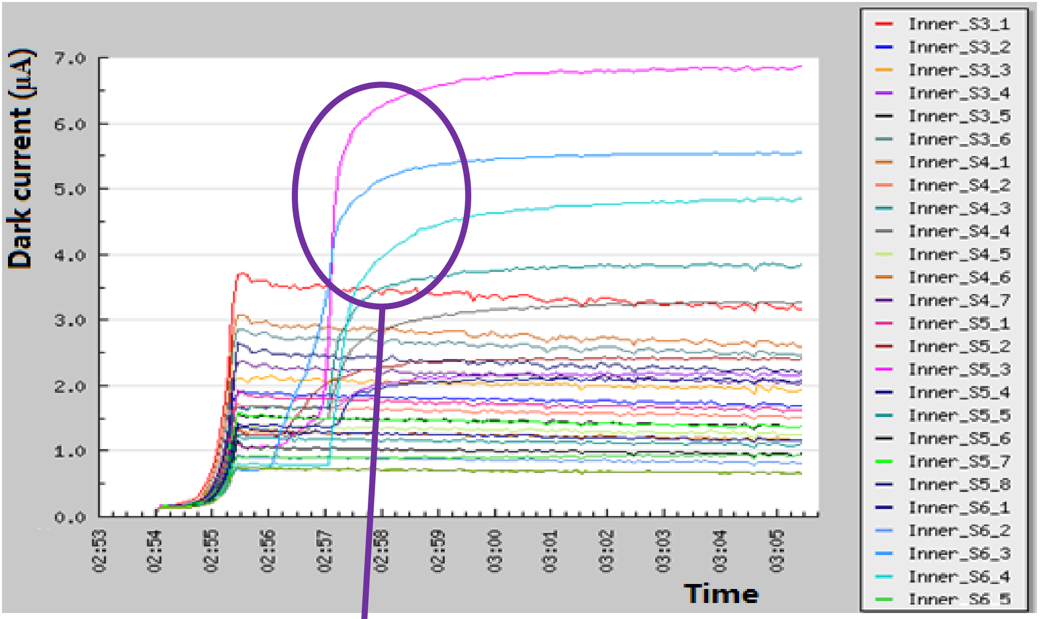
- Cathode aging (Discharge): Malter effect
  - Insulating polymer deposited on field wires prevents the neutralization of ions, resulting in field strength increase
  - Electrons are extracted from the field wire and generate avalanches at the sense wires
  - More ions enhance the surface electric field of the shell
  - Forms a self-sustaining discharge
  - Related to gas impurities, surface defects or contamination of wires
  - Triggered by high radiation intensity and high gas gain



- Anode aging (Gas gain reduction)
  - Deposits on the anodes cause a gain loss due to the increase in effective diameter of the sense wires
  - The gains of the cells decrease with the increase of the cell accumulated charges year by year
  - Related to accumulated charges of the sense wires and other correlated parameters

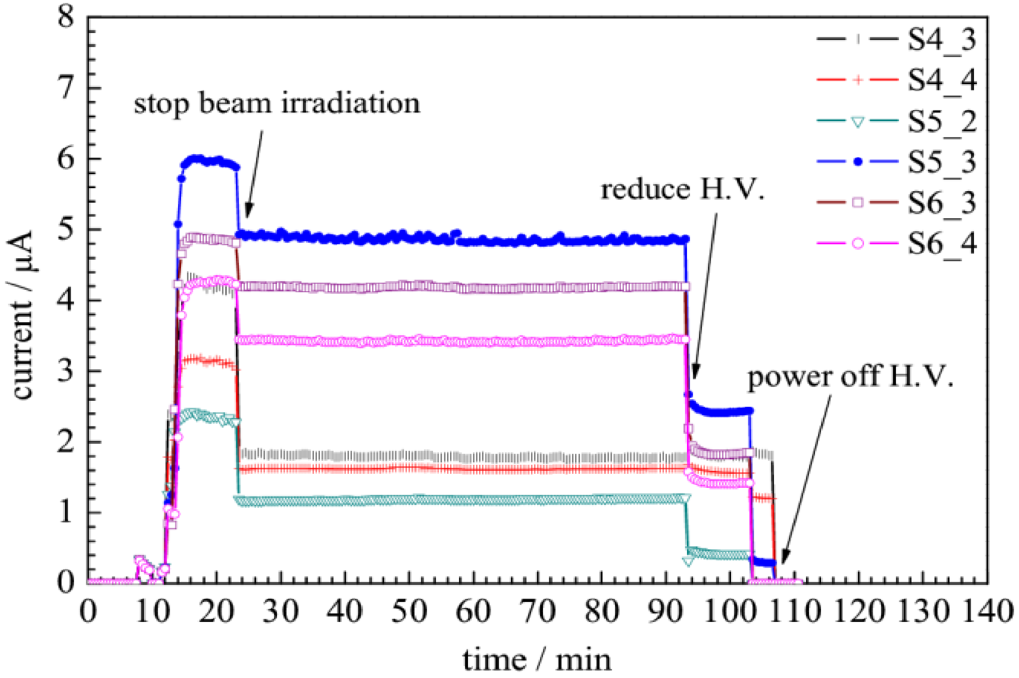


Cathode aging in MDC



Malter discharge in Jan. 2012

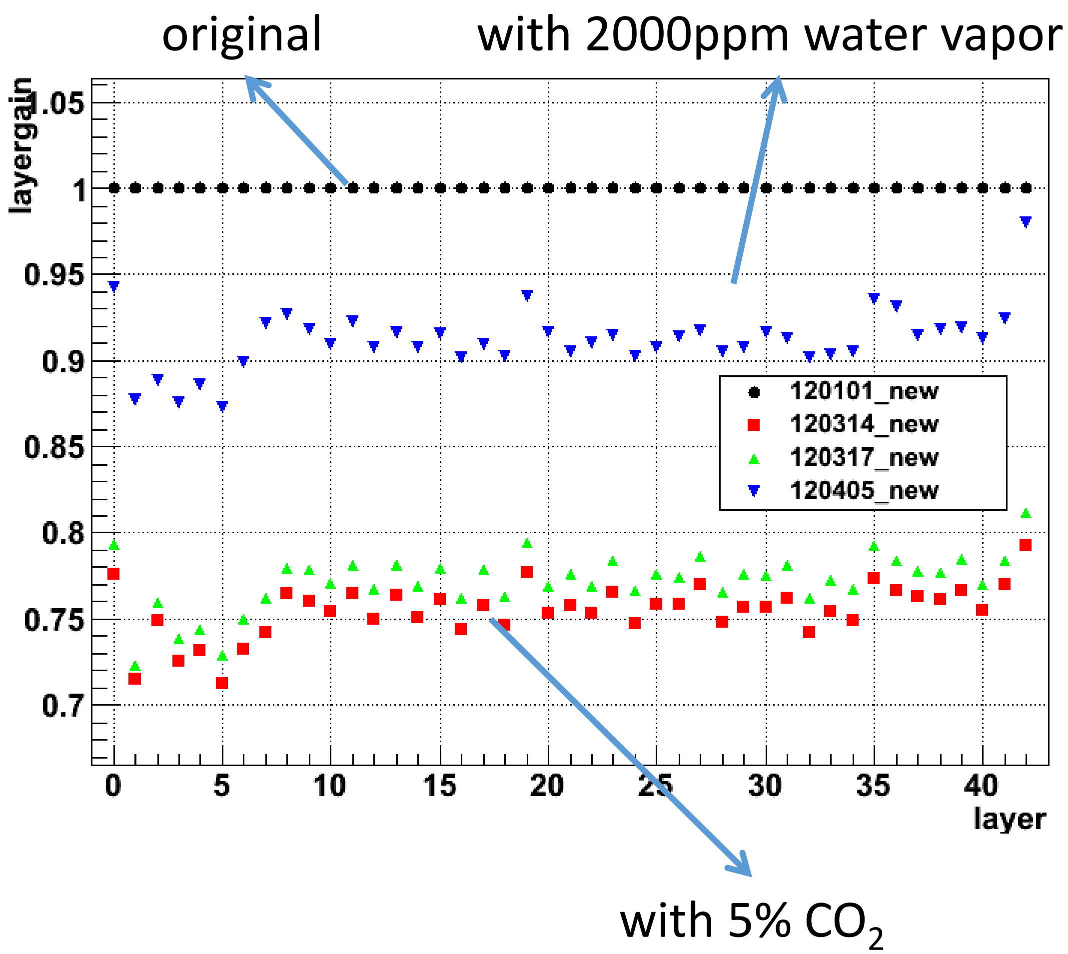
- Sharp increase in currents in parts of cells in inner chamber
- First found in L7-3, L8-3, rapidly spread to adjacent cells , but did not to cells in outer chamber (independent field wire layers)
- A self-sustaining discharge, non-local because of high infectivity



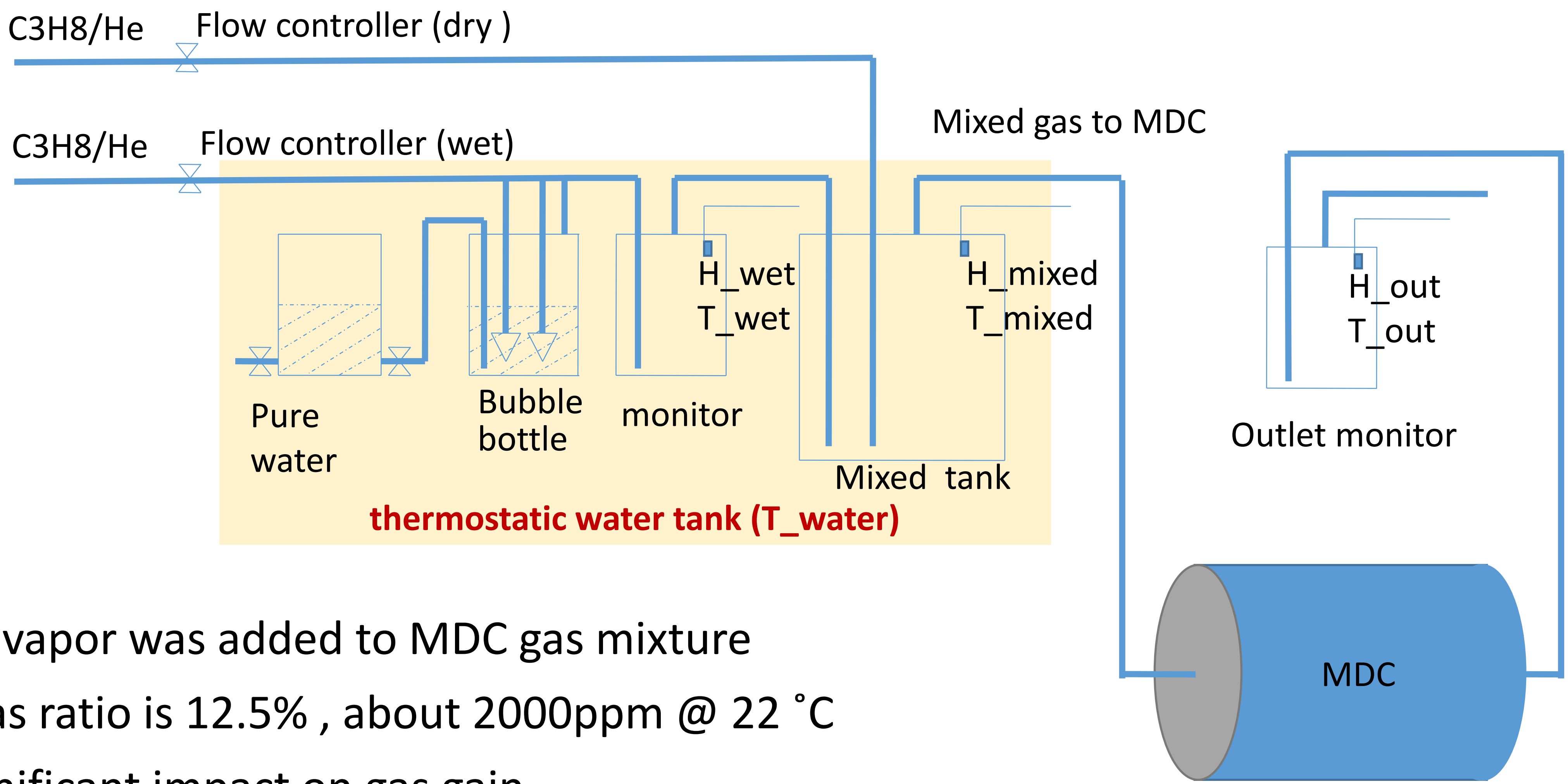
- Test with beam irradiation
  - Discharge occurred at very beginning
  - Did not disappear even after stopping beam
  - Still existed after reducing high voltage
  - Disappeared after powering off HV
- Confirmed to be Malter discharge

CO2 additive to MDC gas

- Added 5% CO_2 to MDC operation gas
- Conducted CO_2 training for about a week with radiation intensity and high voltage increased step by step
- MDC worked stably with 5% CO_2 for about one month (From Feb. 27th to March. 30th)
  - Malter discharge occurred one time (March. 5th)
  - The gas gain decreased about 23%



Water vapor additive to MDC gas



- Water vapor was added to MDC gas mixture
- Wet gas ratio is 12.5% , about 2000ppm @ 22 ˚C
- No significant impact on gas gain
- MDC has been working stably up to now , and no Malter discharge has been observed

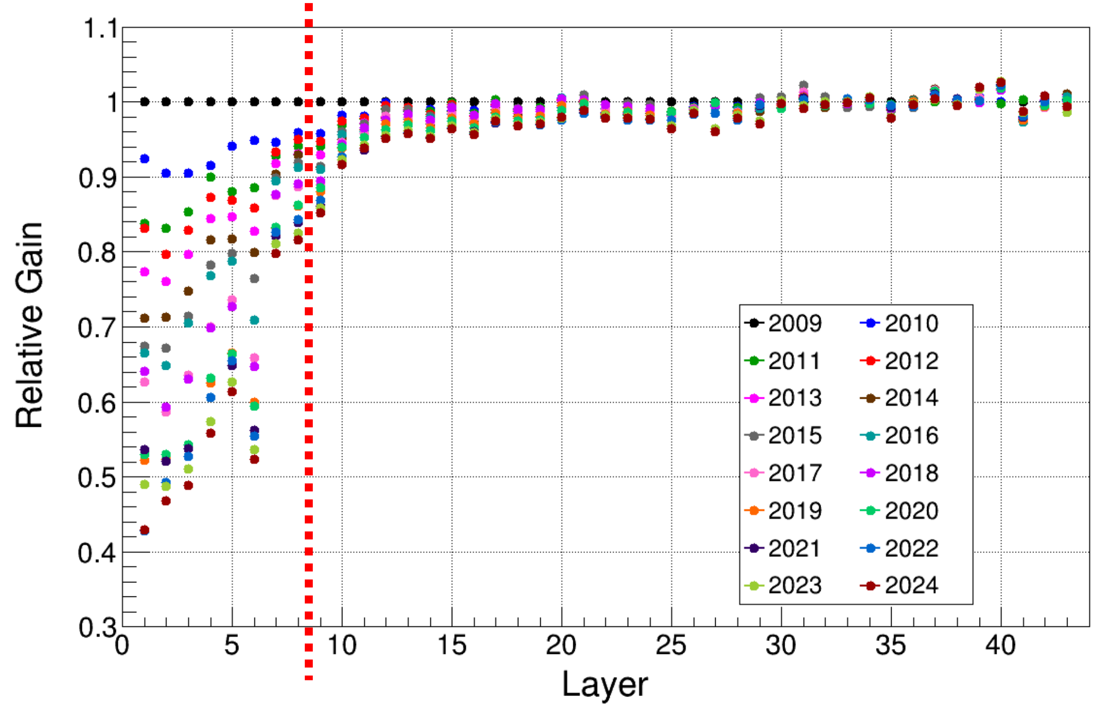
Anode aging in MDC

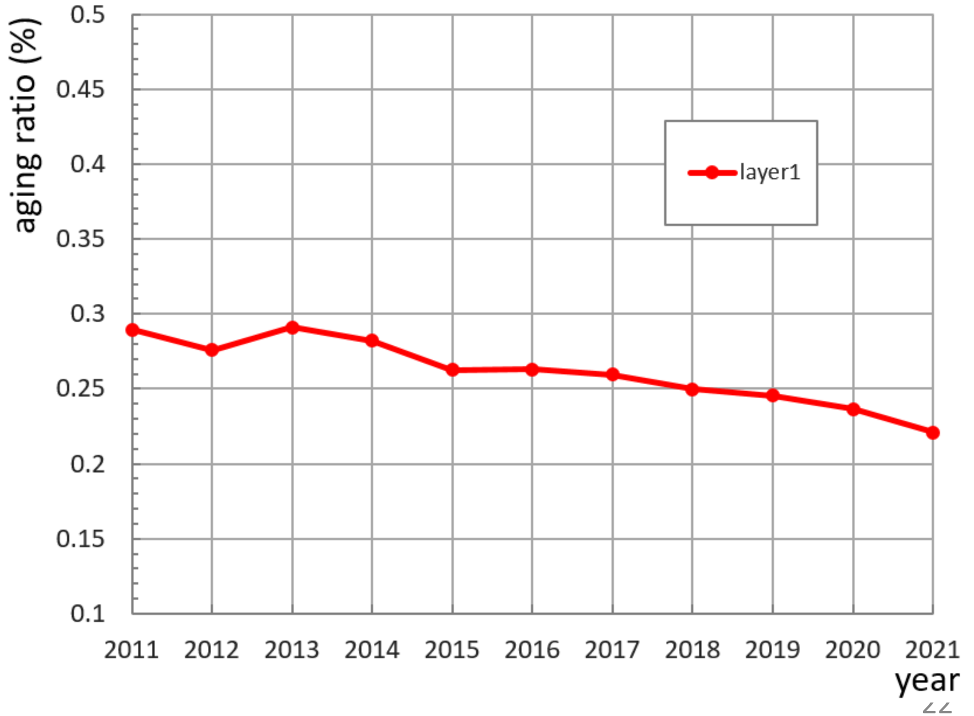
- Gains of inner chamber dropped by >50% for the first layer cells
- No significant change in gain for outer layers

- Aging ratio: $R = -\frac{1}{Q} \cdot \frac{\Delta G}{G} \% \Big/ (mC / cm)$

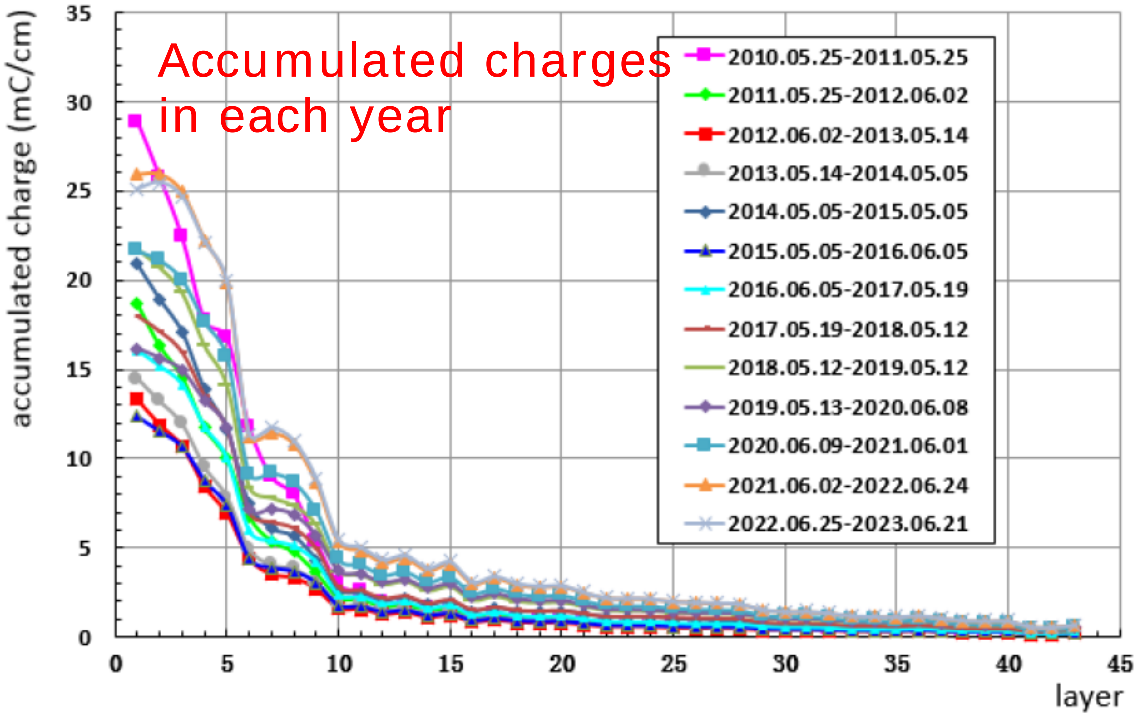
Confirmed that aging ratio is not a constant which depends on correlated parameters, such as gas gain, radiation intensity…

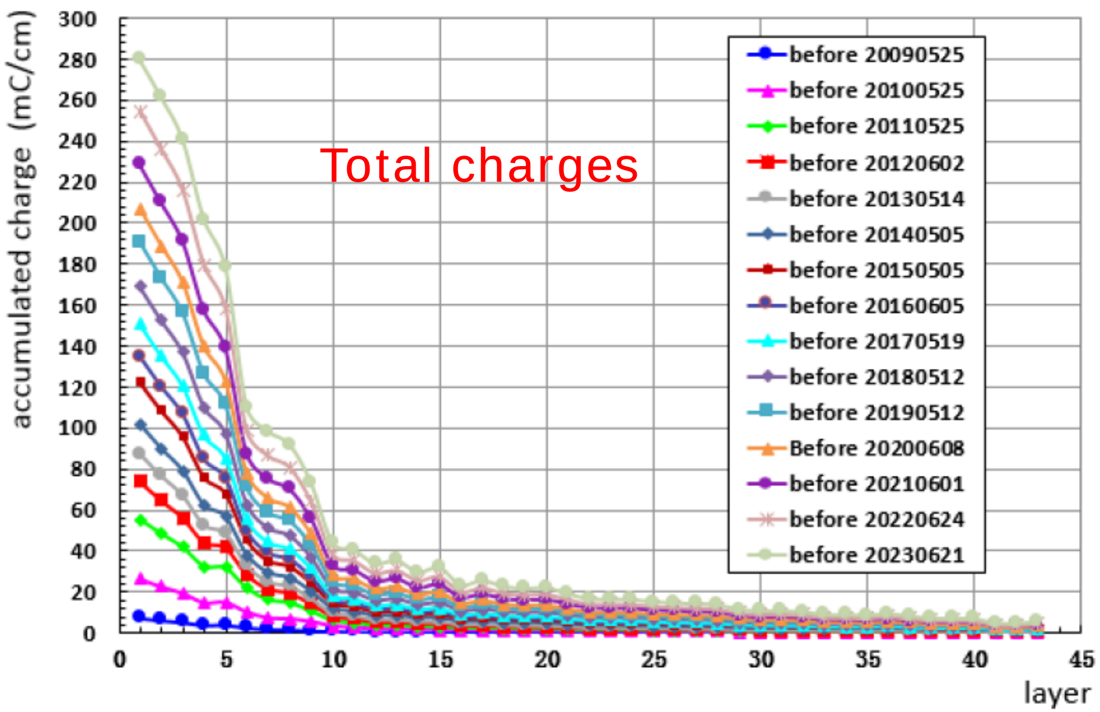
Inner chamber Inner chamber





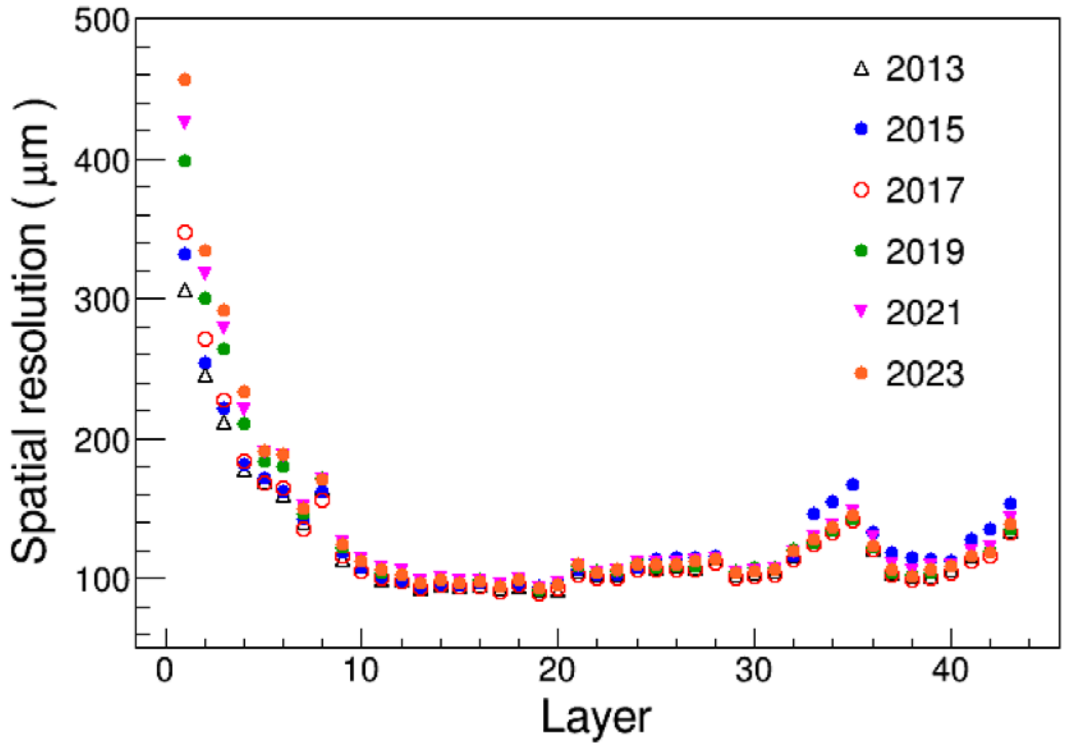
Accumulated charges

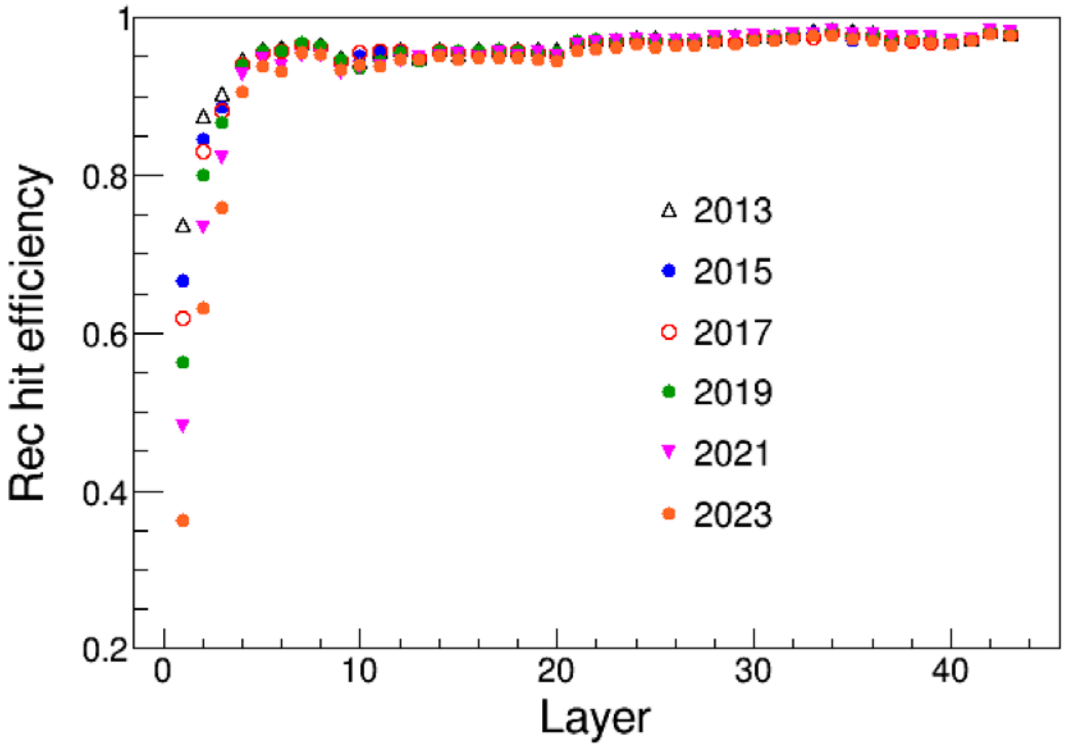




- Integrate currents of each cell to get accumulated charges, accumulated charges increase year by year
- Total charges are about 280mC/cm for the first layer
- Total charges decrease rapidly for the cells far away from the IP

MDC spatial resolution and efficiency

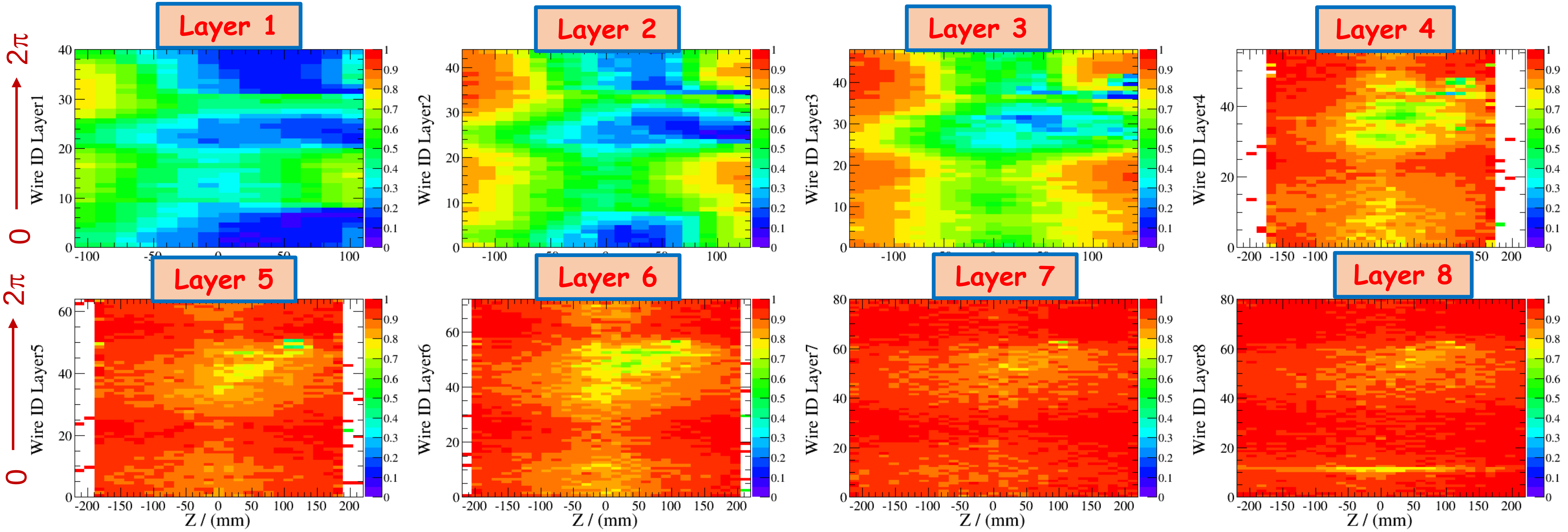




- The resolution of the inner chamber has significantly decreased
  - Decrease in gain caused by aging
  - Low voltage setting leads to low gain for the first four layers
- Almost no changes for the outer chamber

- Hit efficiency of the first three layers decreased year by year
- No significant decrease for most layers

Rec hit efficiency



- The efficiency of the first three layers are nonuniform
- Some region is quite low (~*20%*) , Signals are lower than threshold

Factors affecting the aging of gas detectors

- Long data-taking periods in high-energy physics experiments
  - Long-term stable operation
  - Consideration of aging detector issues
- Aging is correlated with multiple highly interdependent parameters and determined by combined factors,
- Aging cannot be accurately characterized solely by integrated charge.

$R = -(1/G)(dG/dQ)$ (% per C/cm)

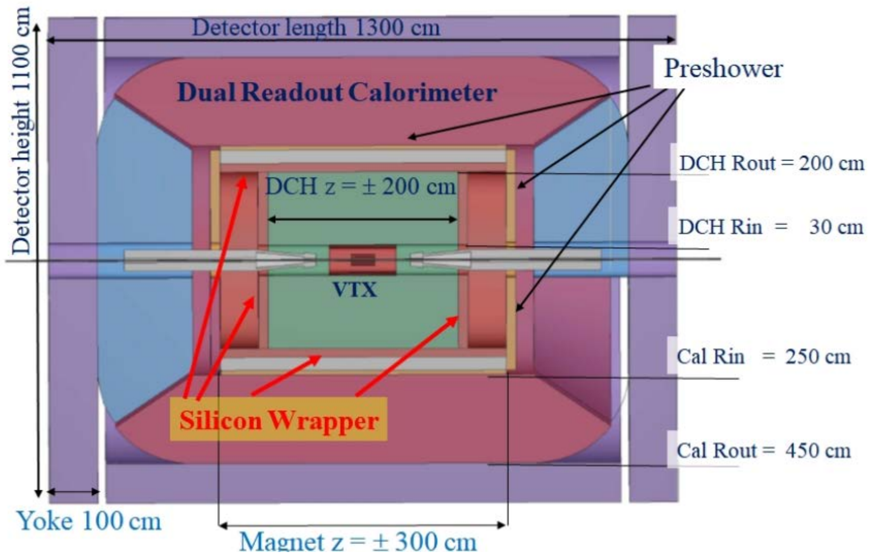
Macroscopic Factors:

- ✓ Gas mixture (gas properties, trace contaminants)
- ✓ Gas flow rate and pressure, exchange rate
- ✓ Electrode geometry / material and electric field configuration
- ✓ Construction materials
- ✓ Radiation intensity
- ✓ Particle type and energy
- ✓ Gas gain
- ✓ Irradiated area size

Microscopic Factors:

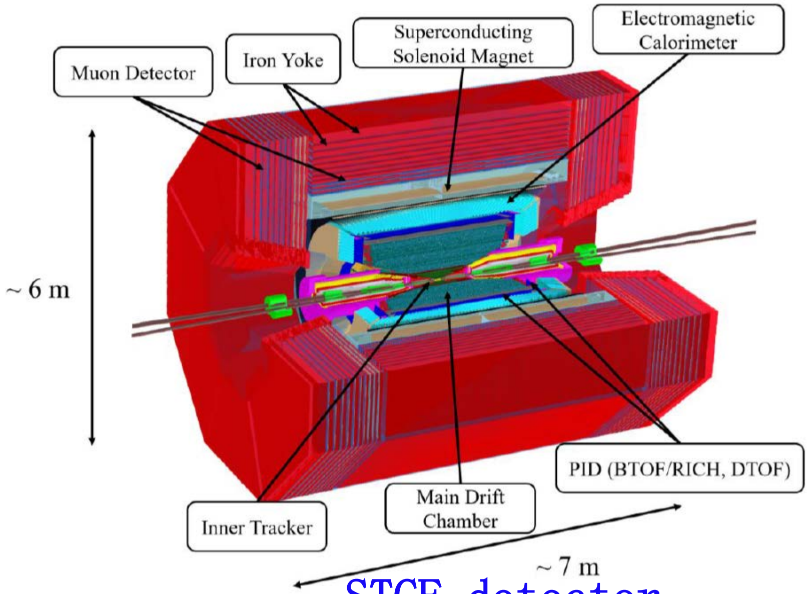
- ✓ Interaction cross section
- ✓ Ionization density
- ✓ Particle type and energy
- ✓ Densities of electrons, ions and free radicals
- ✓ …

Drift chamber for future high energy physics experiments

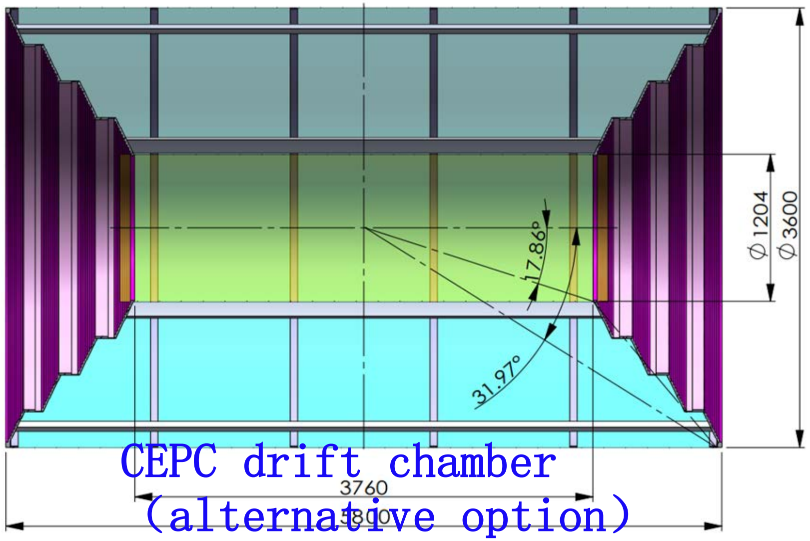


IDEA for CEPC and FCC-ee

ALLEGRO for FCC-ee



STCF detector

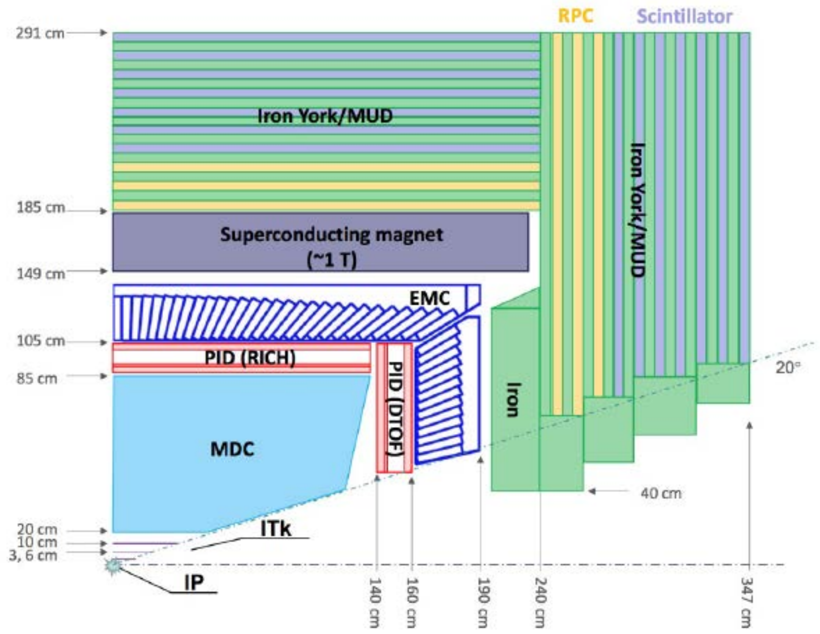


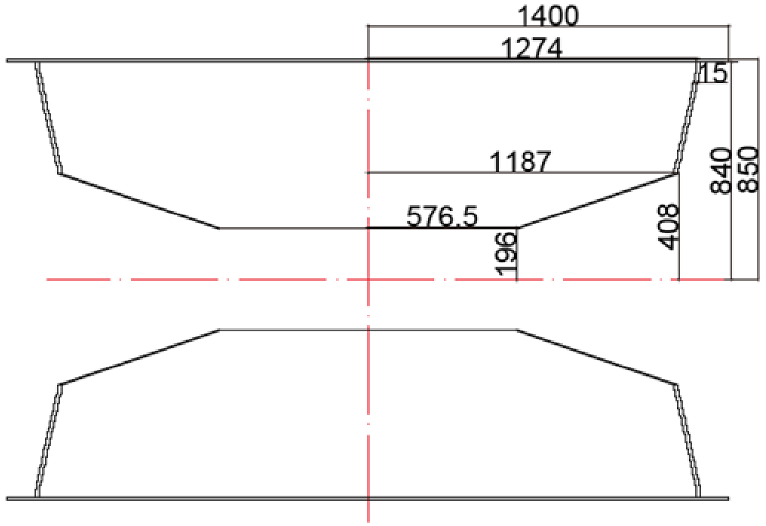
CEPC drift chamber
(alternative option)

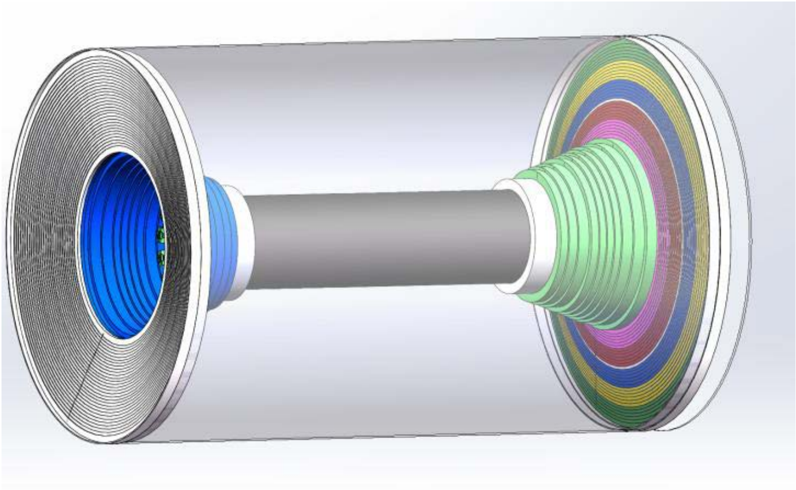
- Studies on drift chamber for CLIC, Fcc-ee, CEPC, STCF
  - Improve the performance of track reconstruction and PID enhance the anti-aging capability
  - Novel technologies and methods (dN/dx)
  - Low material budget: develop new materials (carbon wires); optimize wire stringing techniques; adopt ultra-light structural designs to minimize multiple scattering

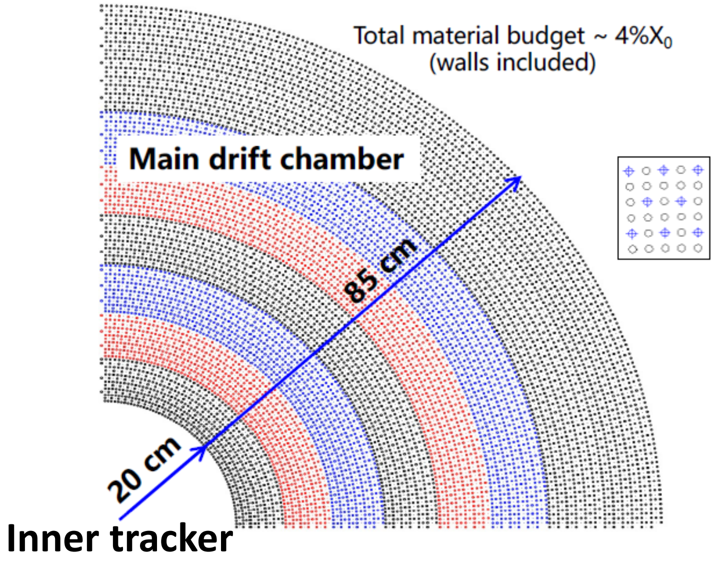
STCF drift chamber（MDCH）

https://indico.pnp.ustc.edu.cn/event/1527/sessions/1137/#20240708, jianbei

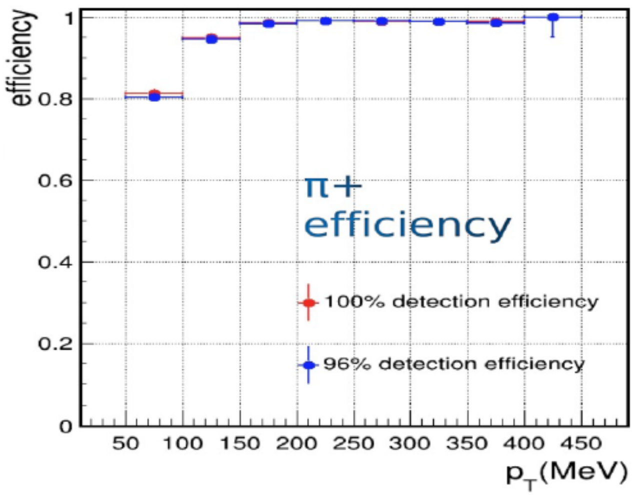




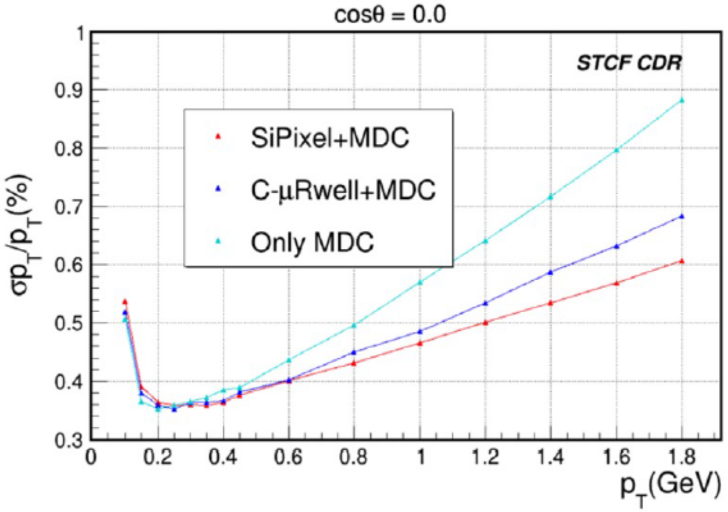




Tracking efficiency



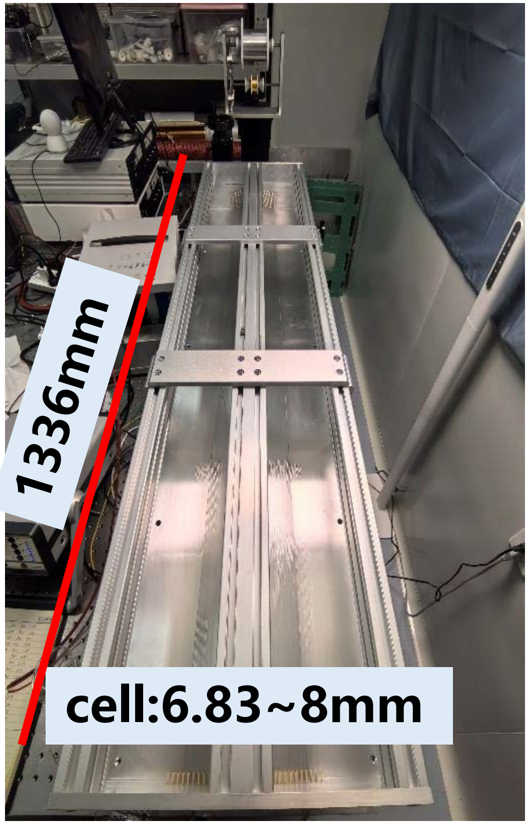
Momentum resolution



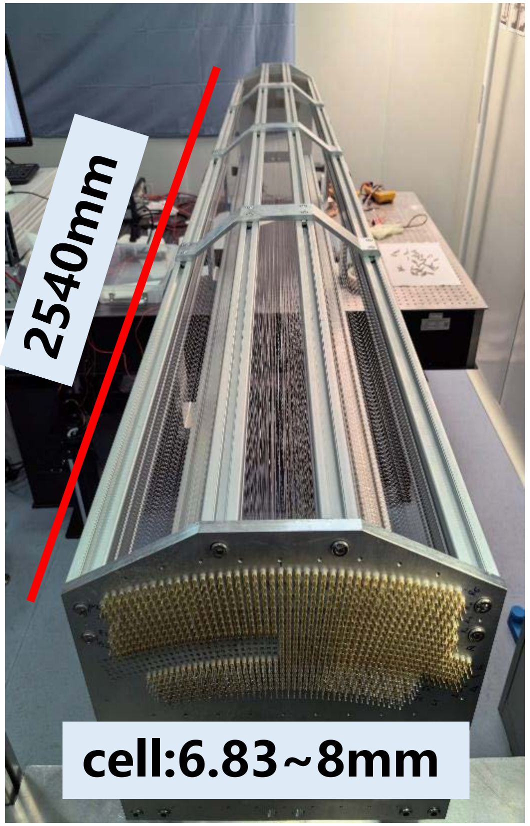
STCF drift chamber（MDCH）

https://indico.pnp.ustc.edu.cn/event/6293/timetable/#all.detailed, liuqian

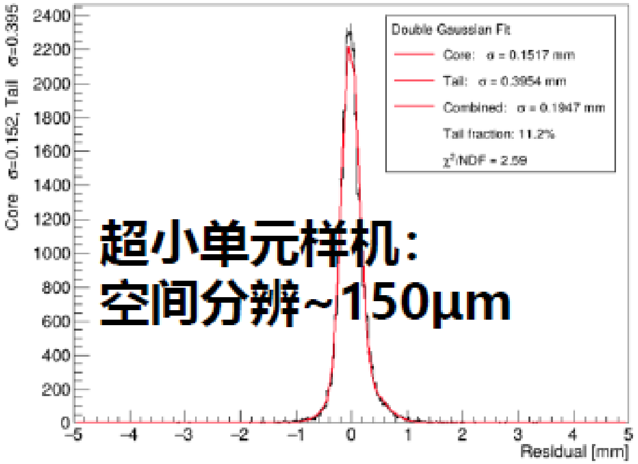
- Maximum drift time : ~250 ns, signal width of MDCH: ~ 500 ns. Within a 500 ns time window, the signal pileup probability of the innermost MDC layer is about 18%, leading to a high signal overlap probability for single channels.
  - (1) Ultra-small cell design (~5 mm)
  - (2) High-counting-rate electronics design

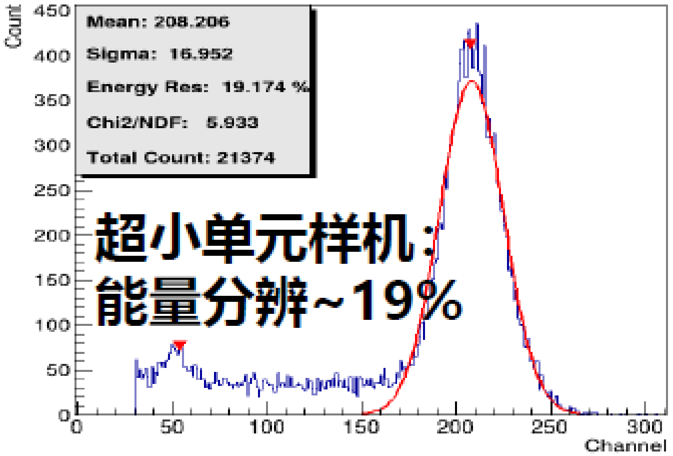


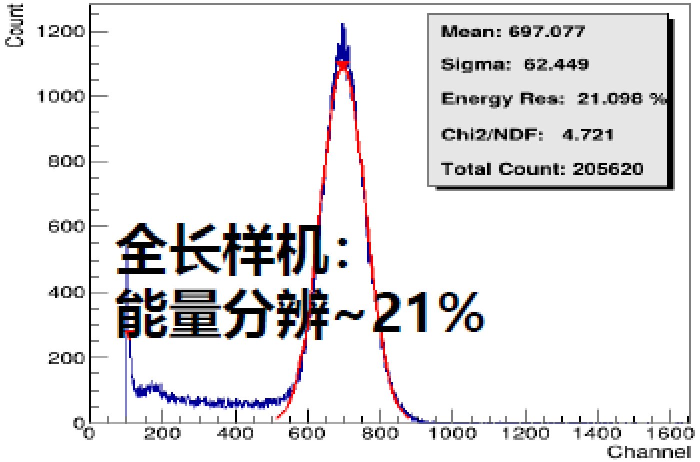
Small-cell prototype



Full-length prototype

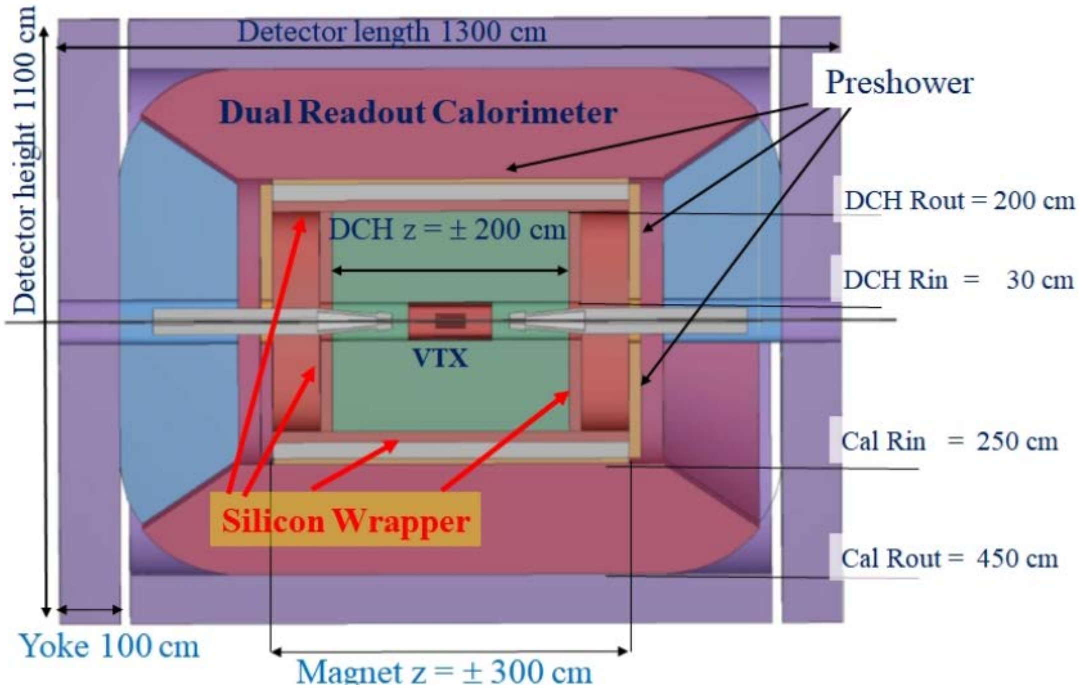


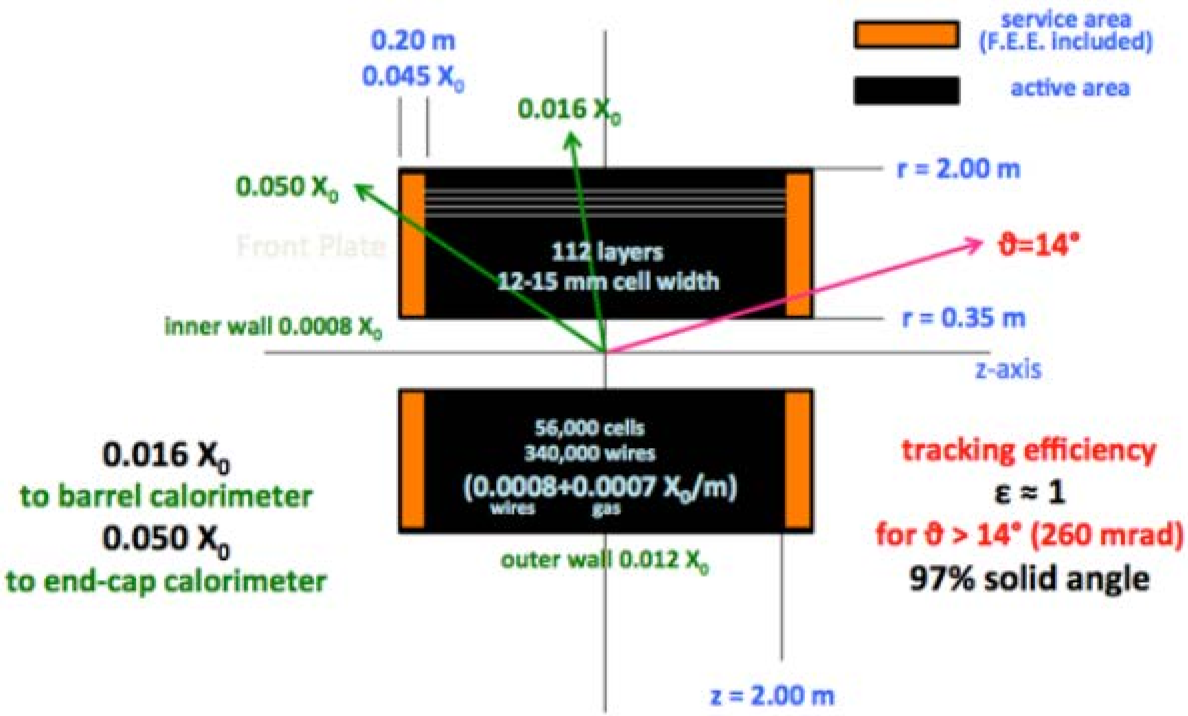




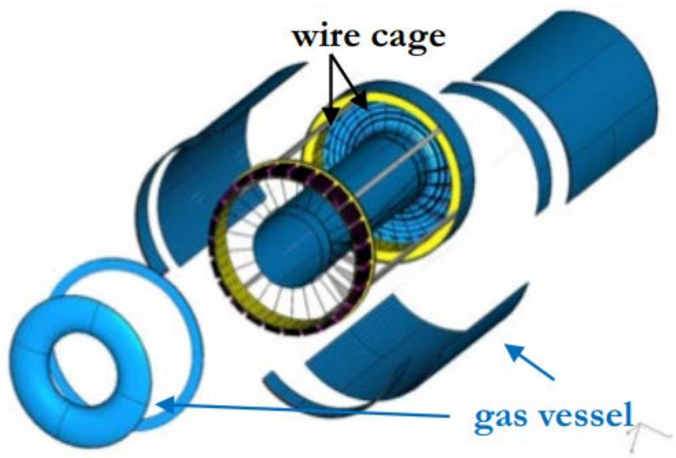
IDEA drift chamber

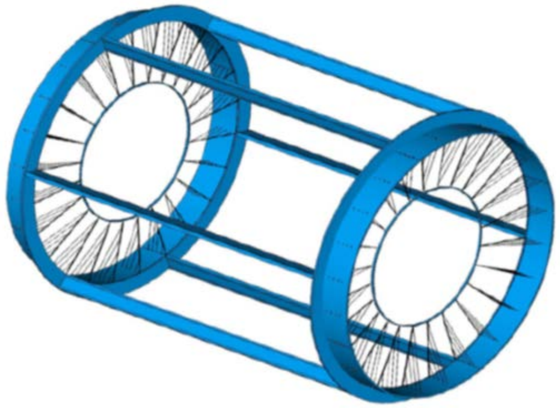
- Large-volume ultra-light drift chambers for FCC-ee and CEPC (the IDEA drift chamber)
  - Suppressed multiple scattering effects
  - High-precision momentum measurement
  - Excellent particle identification performance via cluster counting of primary ionization (dN/dx)
- Its design originates from the DAFNE KLOE drift chamber and its latest variant deployed for the MEG II experiment

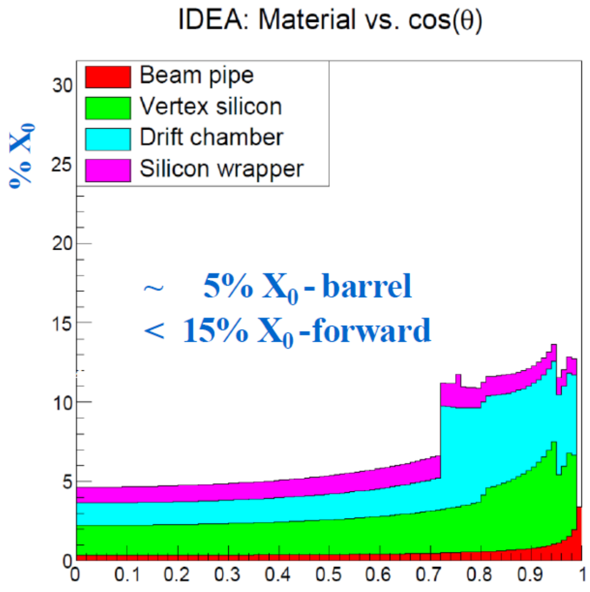


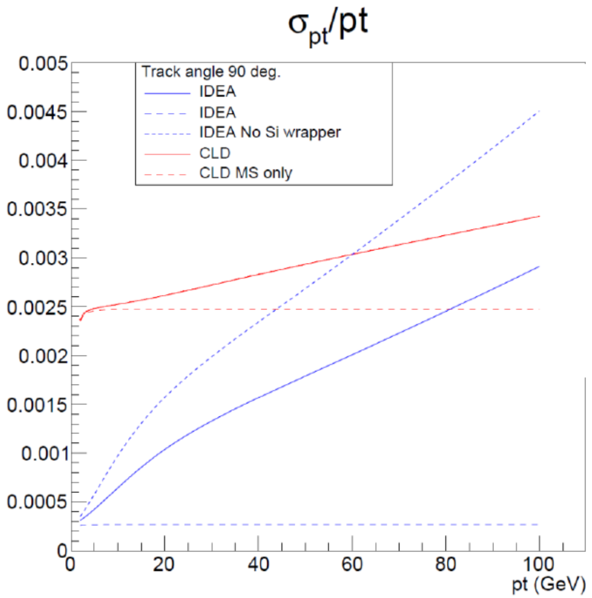


IDEA drift chamber

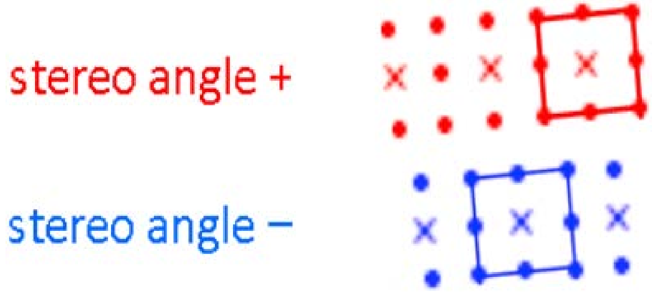




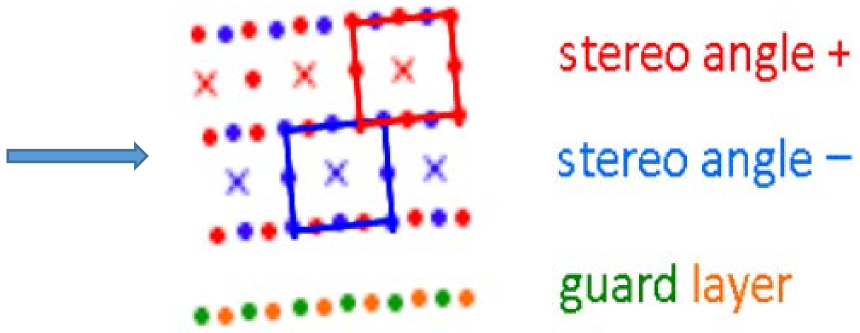




- Low material budget design



field/signal wire ratio : 3:1

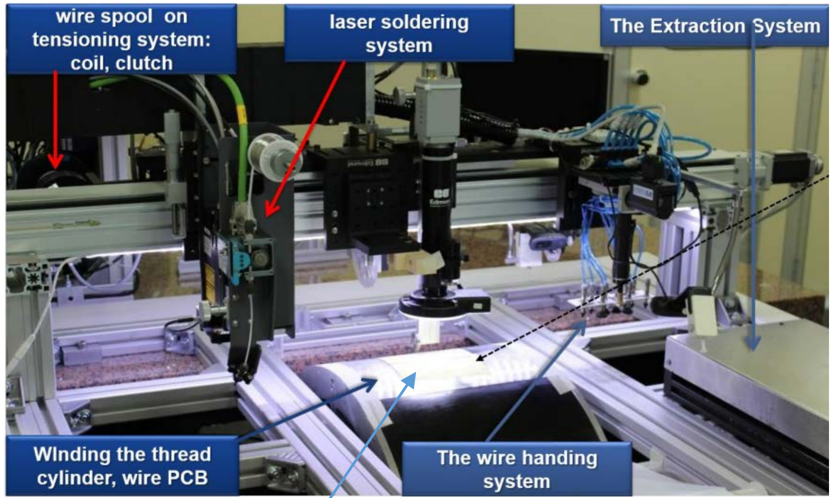


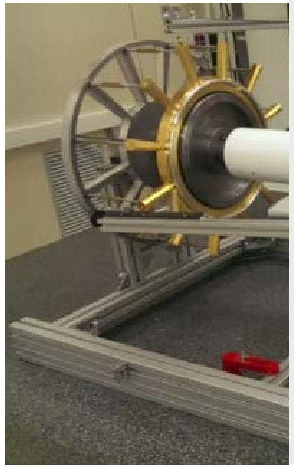
field/signal wire ratio : 5:1

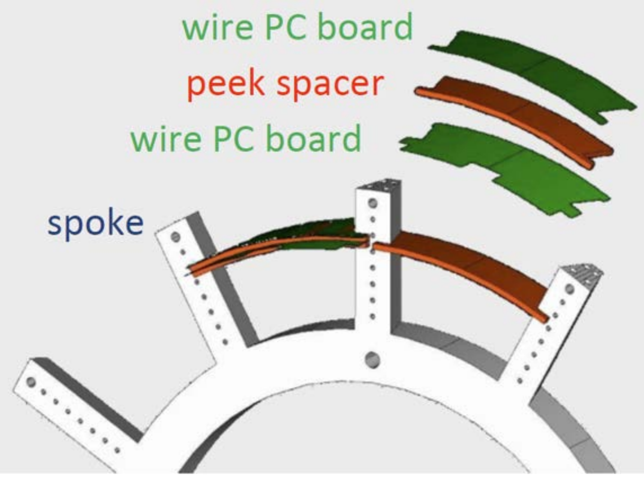
- Small cells with high wire density
- More field wires per cell, enabling the use of thinner field wires
- High-density wire stringing requires unconventional wiring procedures and a feedthrough-free wiring system

MEG II drift chamber

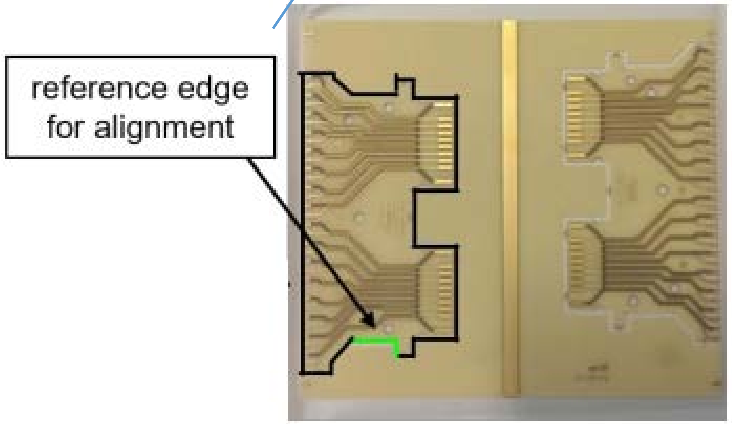
- No Feed-through
- Fix the wires on the PCB by soldering
- Handing process: extracts the multi-wire layers from the wiring system and places them in a storage / transport frame
- Complicated assembly tooling and procedure

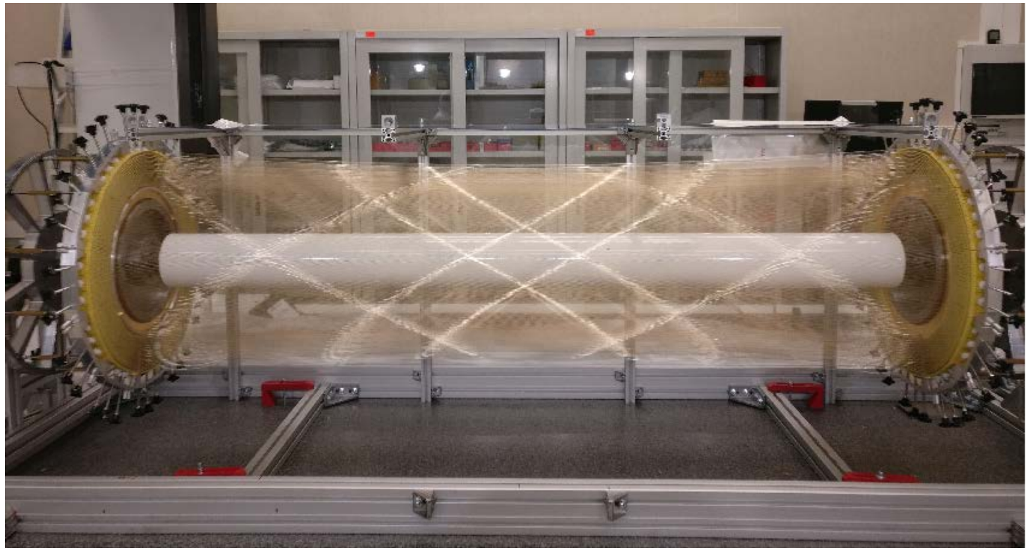






- length: 1.91 m
- radius: 17 cm- 29 cm
- 10 concentric layers
- Cell size : 6.6 mm -9.0 mm
- Total number of cells: 1920
- Total number of wires 13056

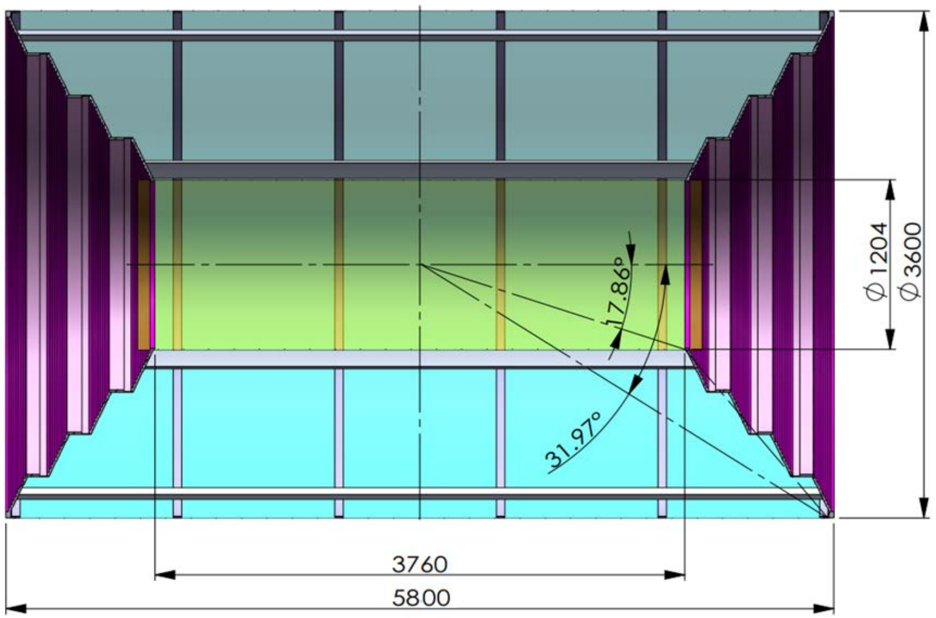




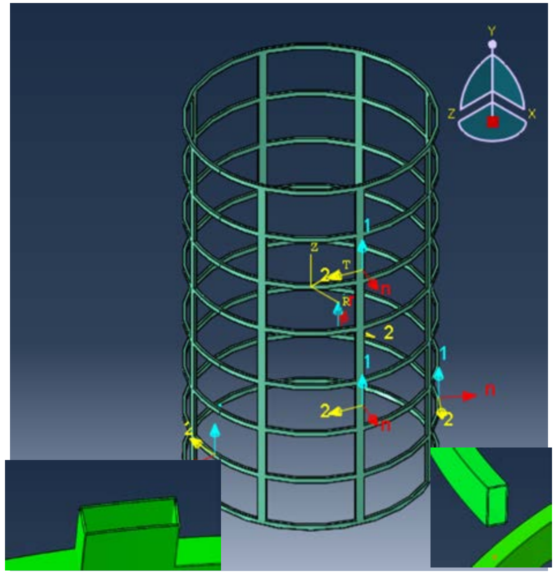
Drift Chamber in CEPC reference detector

- PID is essential for CEPC, especially for flavor physics study

- Drift chamber is an alternative option for CEPC gaseous tracker in CEPC reference detector design
- Besides momentum resolution, PID capability is another important parameter to be optimized
- Design goals: Provides better than 3σ separation power for K/π with momentum up to 20GeV/c



Light carbon fiber frame structure design

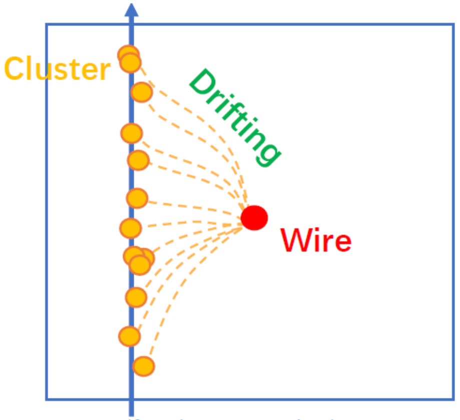


Preliminary design parameters

R extension	600-1800 mm
Length （cosθ=0.85）	5800 mm
inner and outer CF cylinder: for gas tightness, without load	Thickness: ~ 300 µm
CF frame structure	8 longitudinal hollow beams + 8 annular hollow beams
Al end plates:	Thickness: 20 mm
Cell size:	~ 18 mm × 18 mm
Layer and cell number:	64 layer and 27623 cells
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC_4H_{10} = 90:10

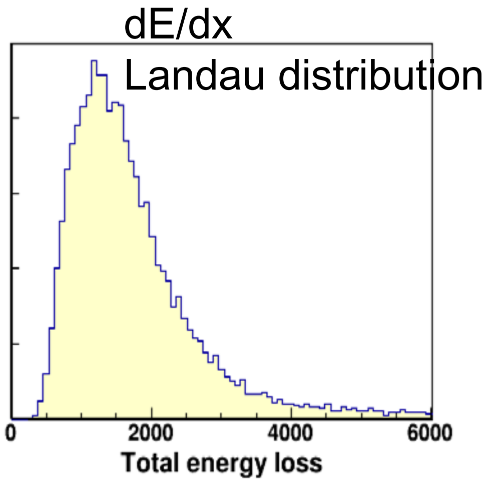
Primary ionization cluster counting (dN/dx)

DC cell

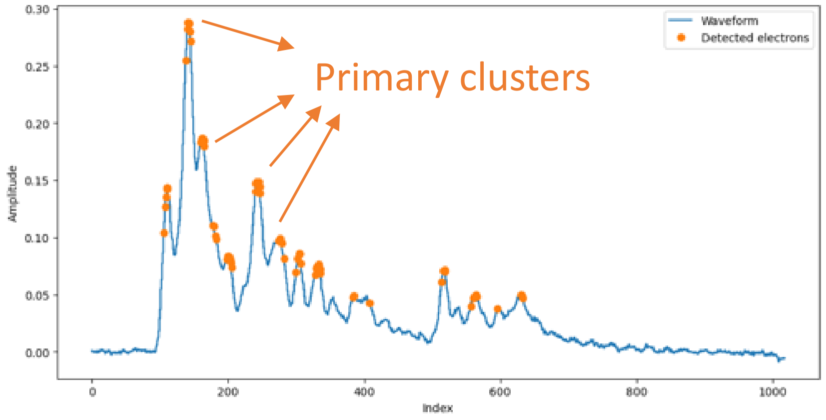


(for demonstration)

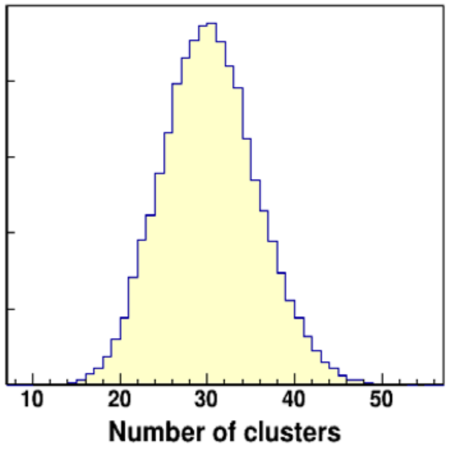
- Measure the number the number of primary ionization over the track.
- Yield of primary ionization follows a Poisson distribution
- Small fluctuations leads to a potential resolution twice better than that of dE/dx (simulation)



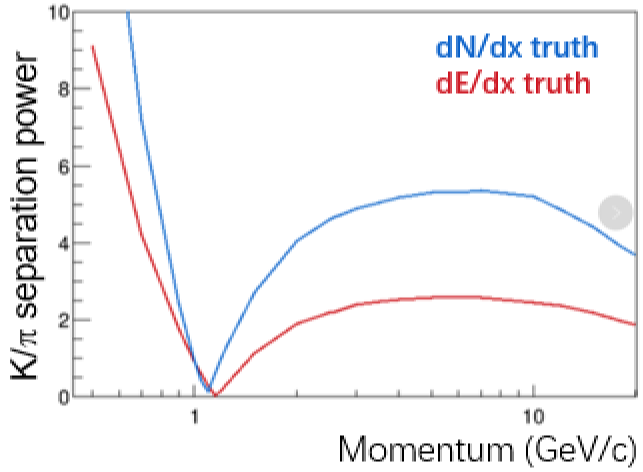
Waveform



Counting clusters



K/π separation power
dN/dx vs dE/dx



Require fast electronics and sophisticated counting algorithm

dN/dx is proposed for ILC, FCC-ee, CEPC

Key issues for DC with dN/dx measurement

- Challenges in waveform precision testing
  - Sufficient time interval between different ionization signals
  - Reducing interference between different ionization clusters
  - Low noise and sufficient SNR
  - Fast signal shaping

✓ Detector optimization: Cell size, HV, and Gas mixture (low drift velocity, low diffusion, suitable ionization density)

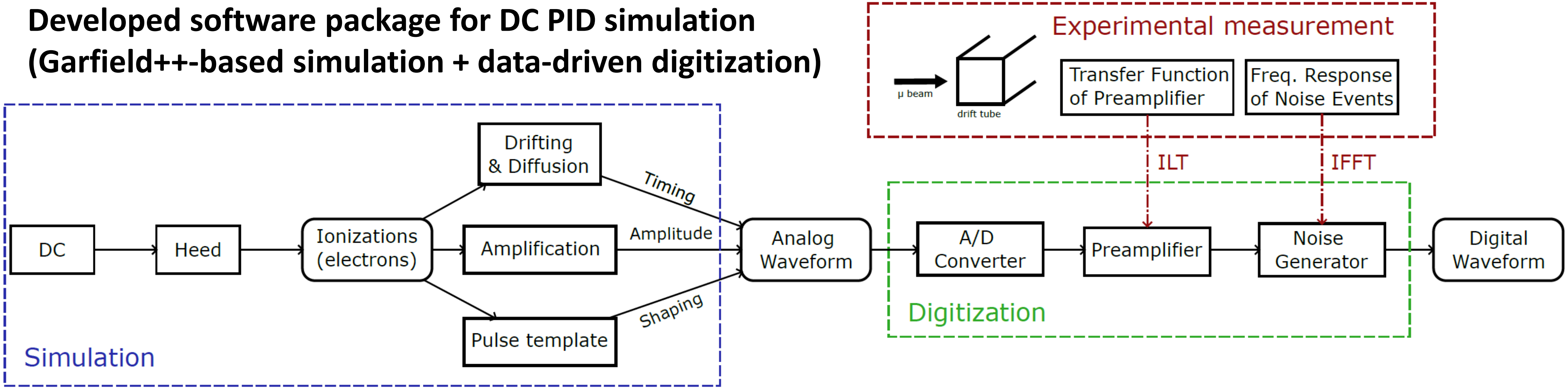
✓ Fast and low noise electronics

- Challenges in reconstruction algorithm
  - Processing piled-up signals
  - Identifying primary and secondary ionization signals
  - Reducing noise impacts

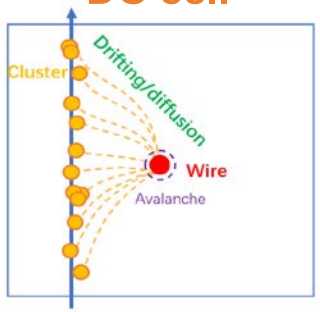
✓ Improve the reconstruction efficiency and purity

Waveform-based full simulation

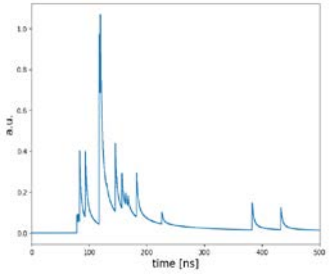
Developed software package for DC PID simulation (Garfield++-based simulation + data-driven digitization)



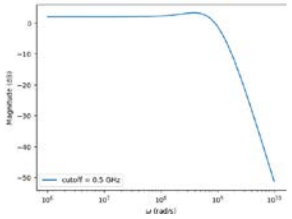
DC cell



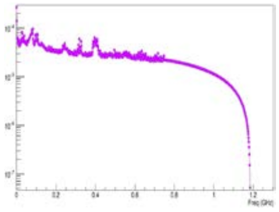
Induced signal



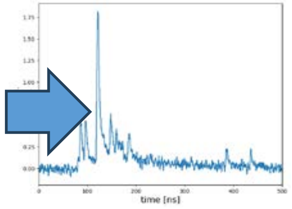
Preamplifier



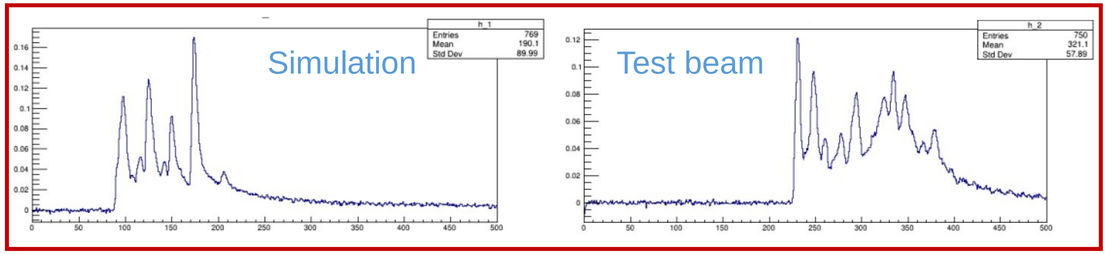
Noise



Waveform



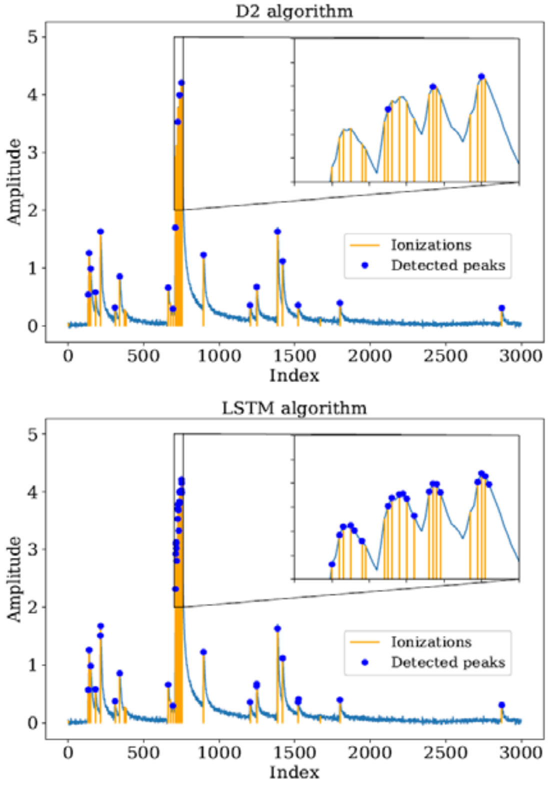
Tuned MC is comparable to data

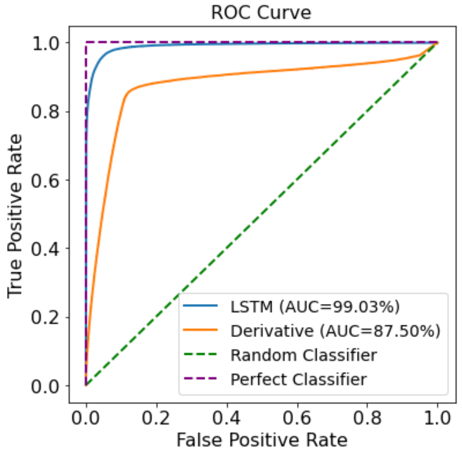


Machine learning reconstruction algorithm

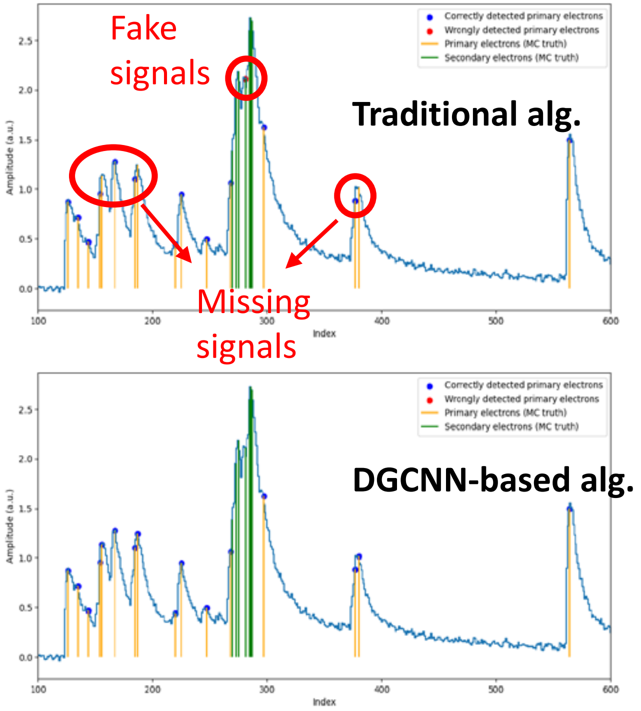
- LSTM-based peak finding and DGCNN-based clusterization
- ~ 10% improvement of PID performance with ML

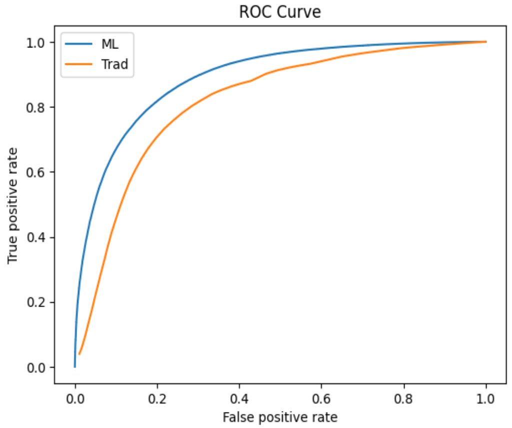
Long Short-Term Memory (LSTM)-based peak finding
higher efficiency than the derivative-based algorithm, especially for the pile-up recovery





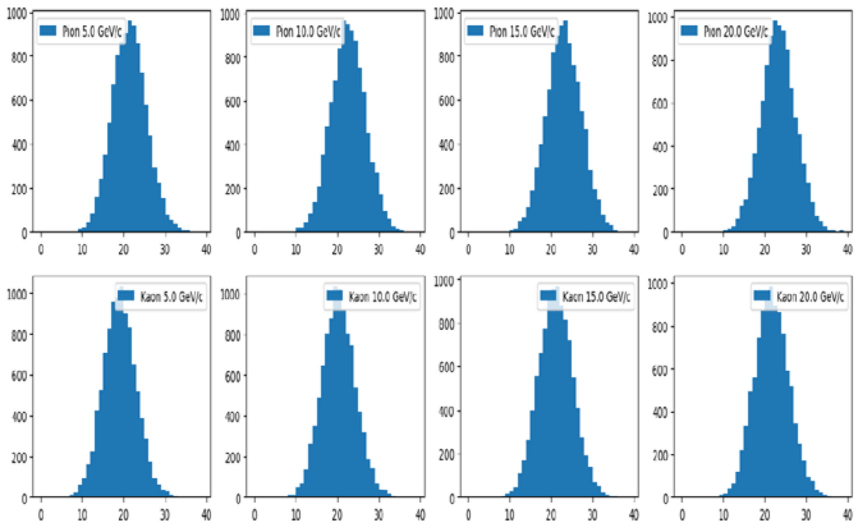
Dynamic Graph CNN (DGCNN)-based clusterization
higher efficiency, and lower fake rate



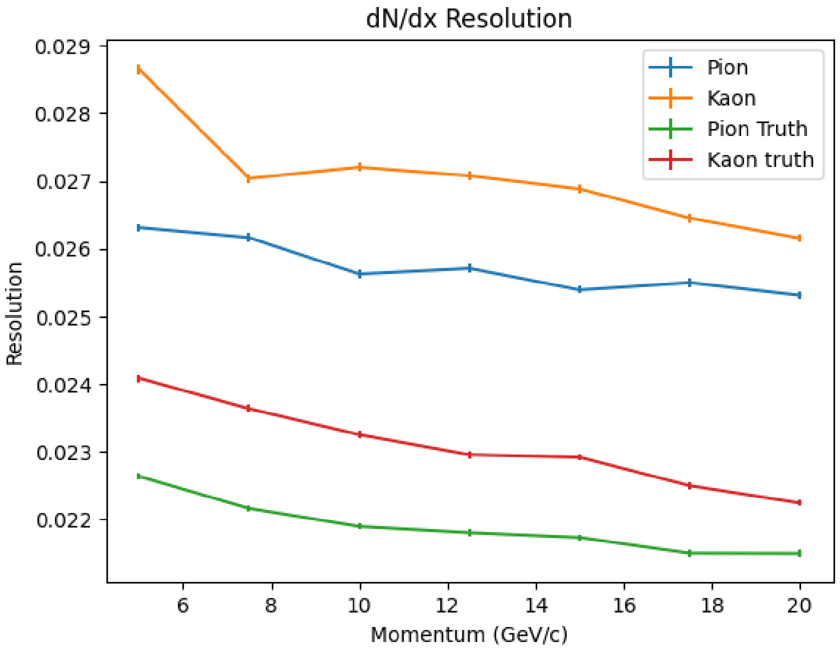


dN/dx resolution of CEPC drift chamber

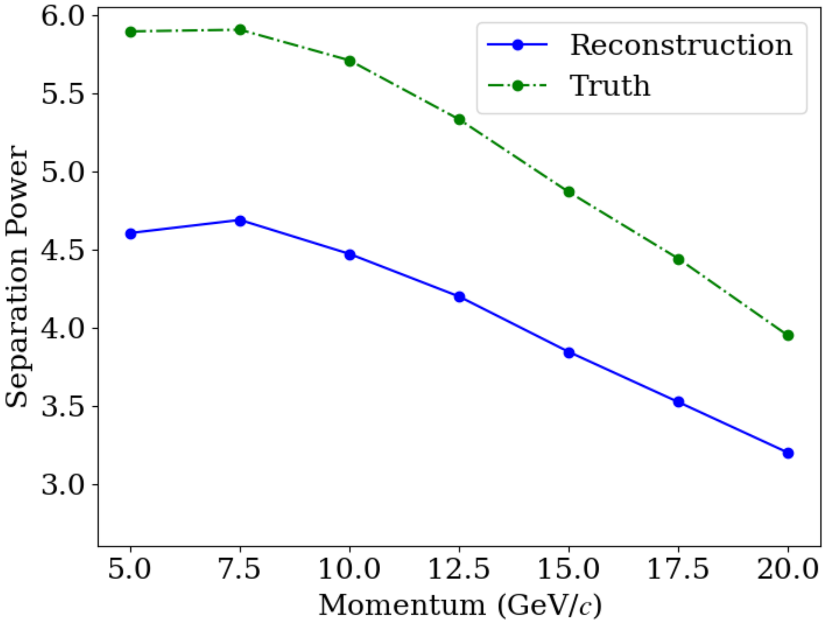
Reconstructed # of clusters distributions



The reconstructed n_{cls} distributions are very well Gaussian-like



- dN/dx resolution (1.2 m track length):
  - 2.5%-2.6% for Pion
  - 2.6%-2.7% for Kaon

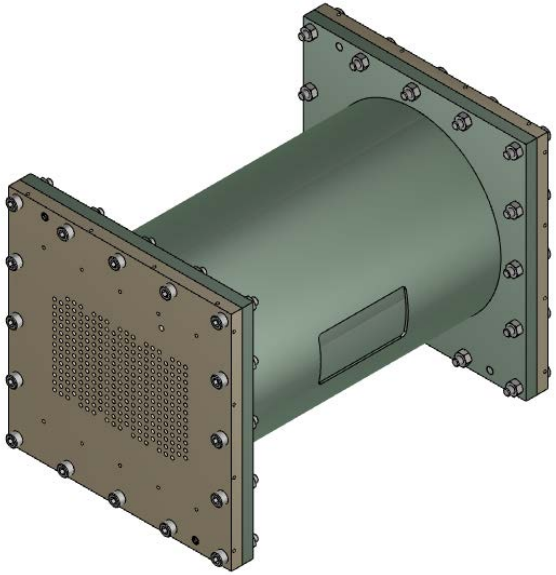


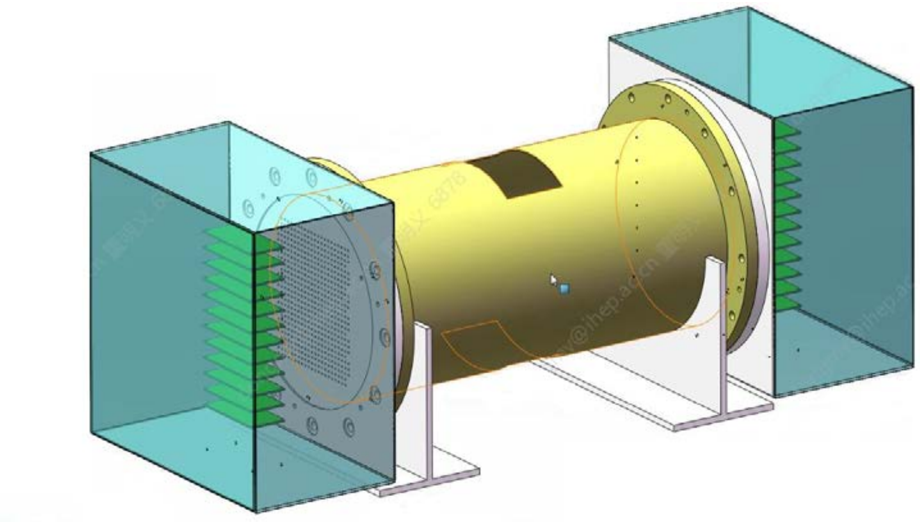
- 1.2 m track length
- For 20 GeV/c K/π, Separation power: 3.2σ

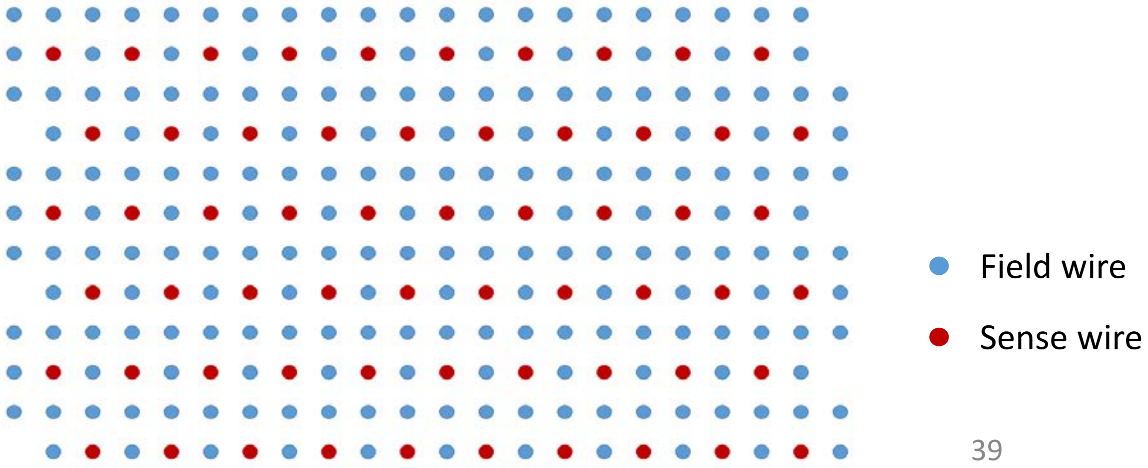
Development of multi-layer DC prototypes

- Prototypes were designed for dN/dx resolution study

	Prototype 1	Prototype 1
Layer number	12	10
Cell number	12×10	10×6
Wire length	60 cm	25 cm
Cell size	18 mm × 18 mm	12 mm × 12 mm
Sense wire parameter	20 µm Au-plated tungsten	20 µm Au-plated tungsten
Field wire paramter	70 µm aluminum	70 µm aluminum

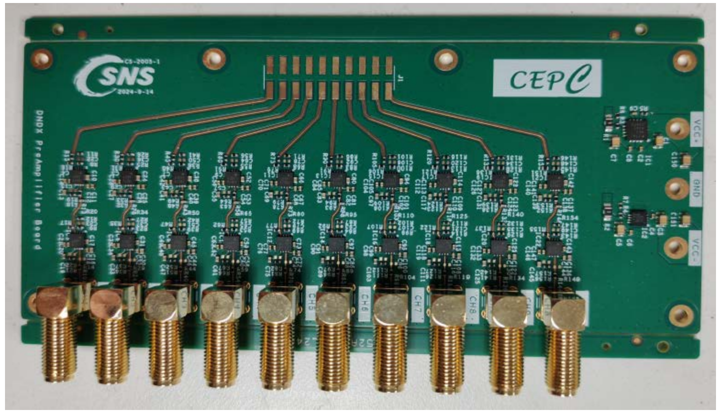


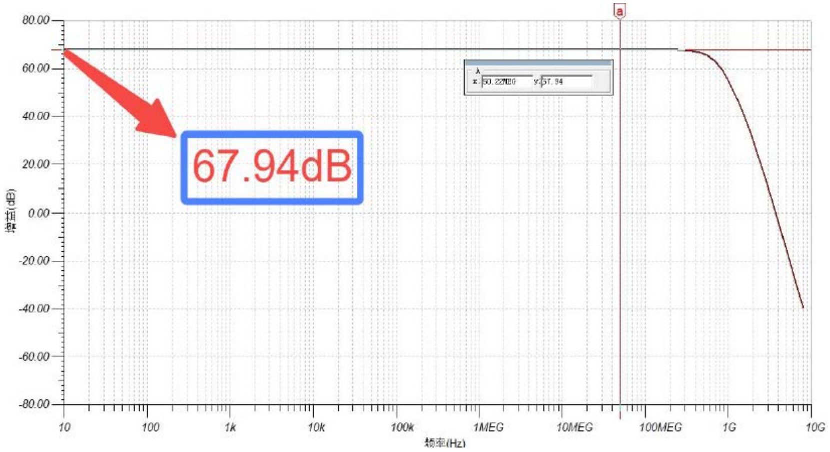


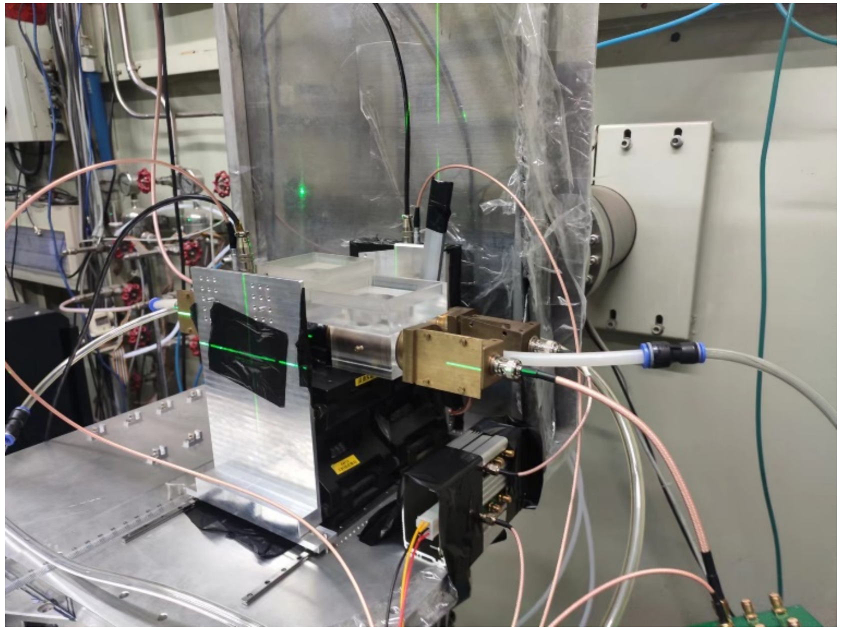


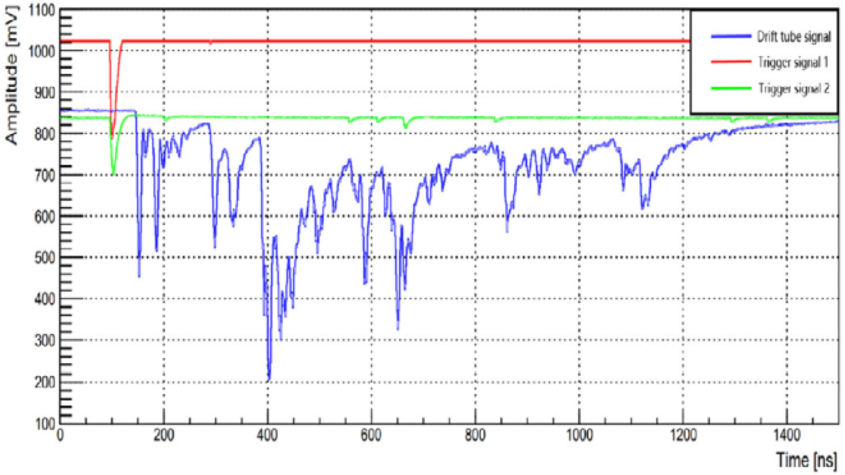
Preamplifier design and test

- Fast current preamplifier based on LMH6629 chips
- High gain, high bandwidth and low noise
  - Current gain： 67.94 dB
  - Bandwidth: 587.74MHz @-3dB
  - Baseline noise: 1.53 mVrms
- Performance was verified through beam test

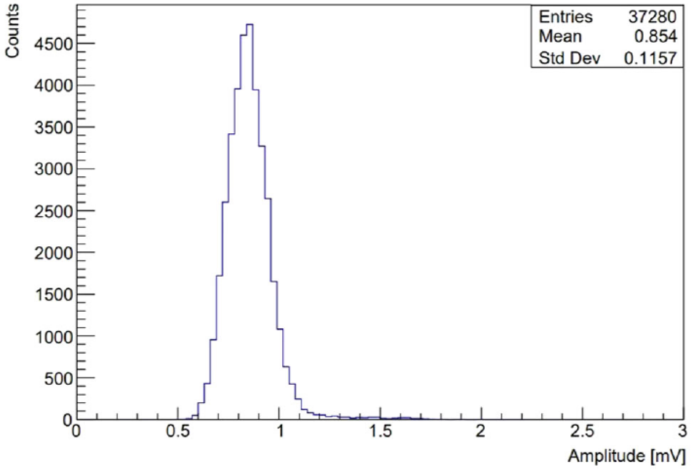








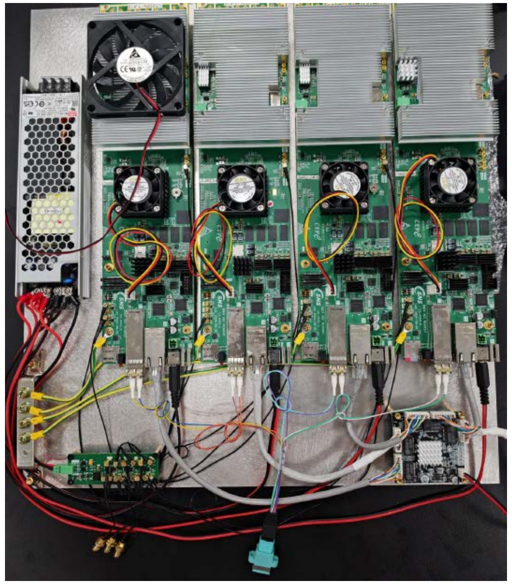
waveform



noise

Readout electronics

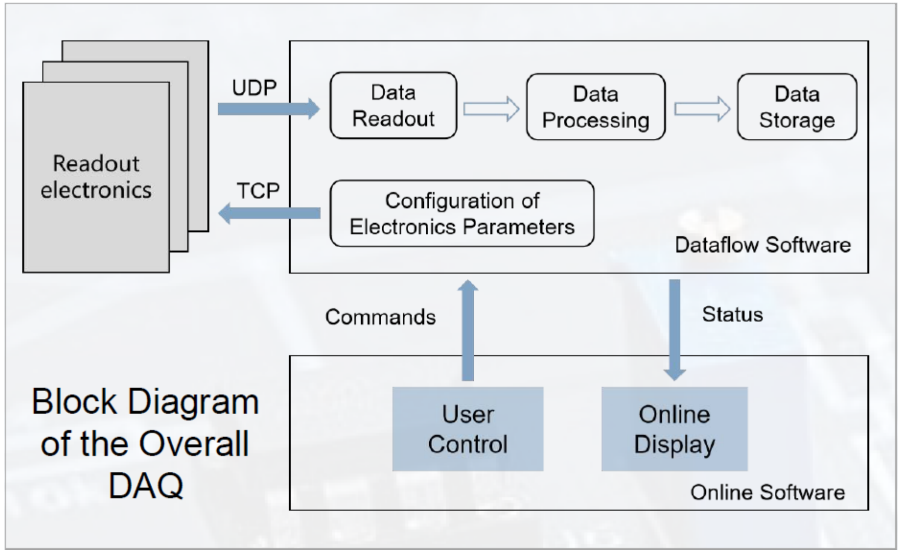
Digitization and FPGA board

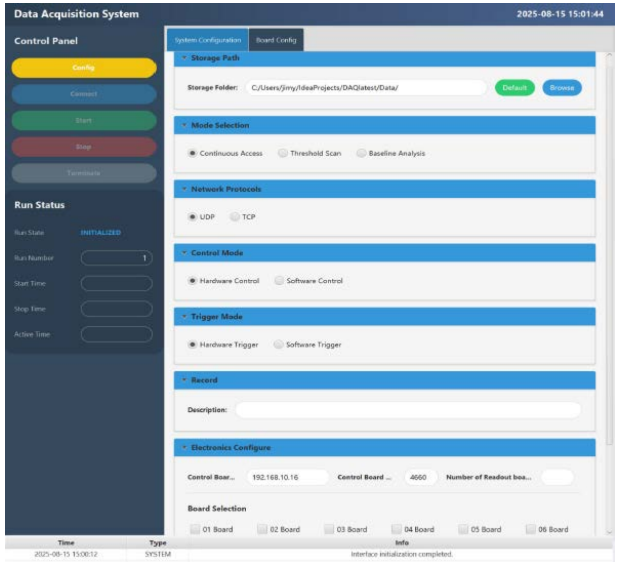


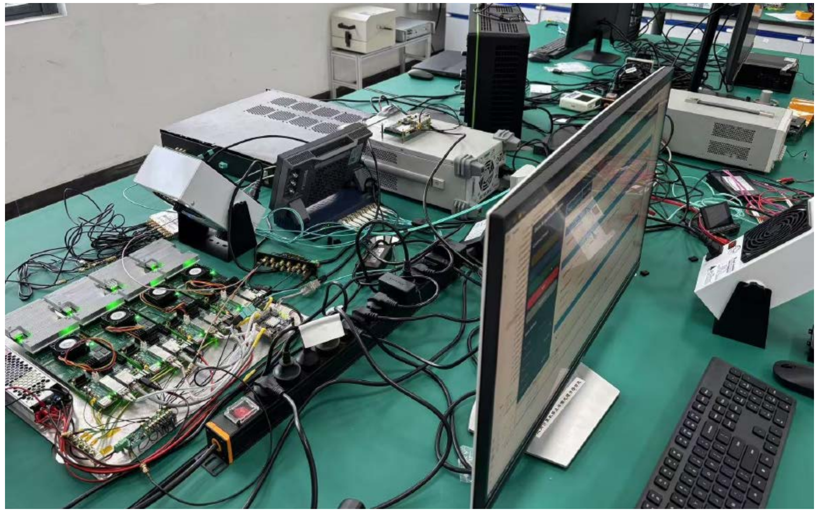
40 channels crate

- ADC mezzanine board
  - Sampling rate: 1.3 Gsps, resolution: 14 bit
  - Power consumption: 750 mW/channel
- FPGA readout board
  - Receive data streams from five AD9695 ADCs via 13 Gbps JESD204B links
  - Send processed data to the DAQ server via 10 Gbps UDP links
- Each crate contains 40 digitization channels

DAQ



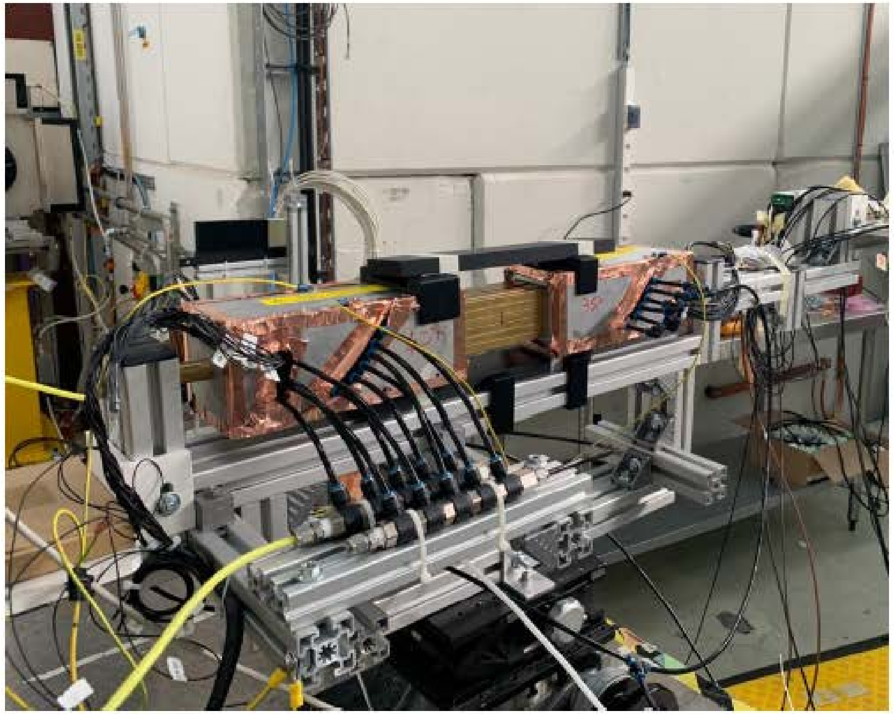




- Transmit data by 10 Gbps UDP
- Configure electronics by 1Gbps TCP
- Dataflow Software
  - Read out , check and save data
  - Configure the electronics, …
- Graphical user interface
  - Commands
  - Run information
  - Run log file
- Online display software
  - Online data process
  - Online waveform display

Beam test at CERN T9 in 2026

Both the IDEA and IHEP CEPC team joined the test and work together



Nicola De Filippis

DRD1 WG1+WG2 workshop on June 16, 2006

https://indico.cern.ch/event/1675383/

Box with 20 drift tubes:

- 1(effective 0.8) and 1.5(effective 1.1) cm cell size
- 20μm Au-plated tungsten

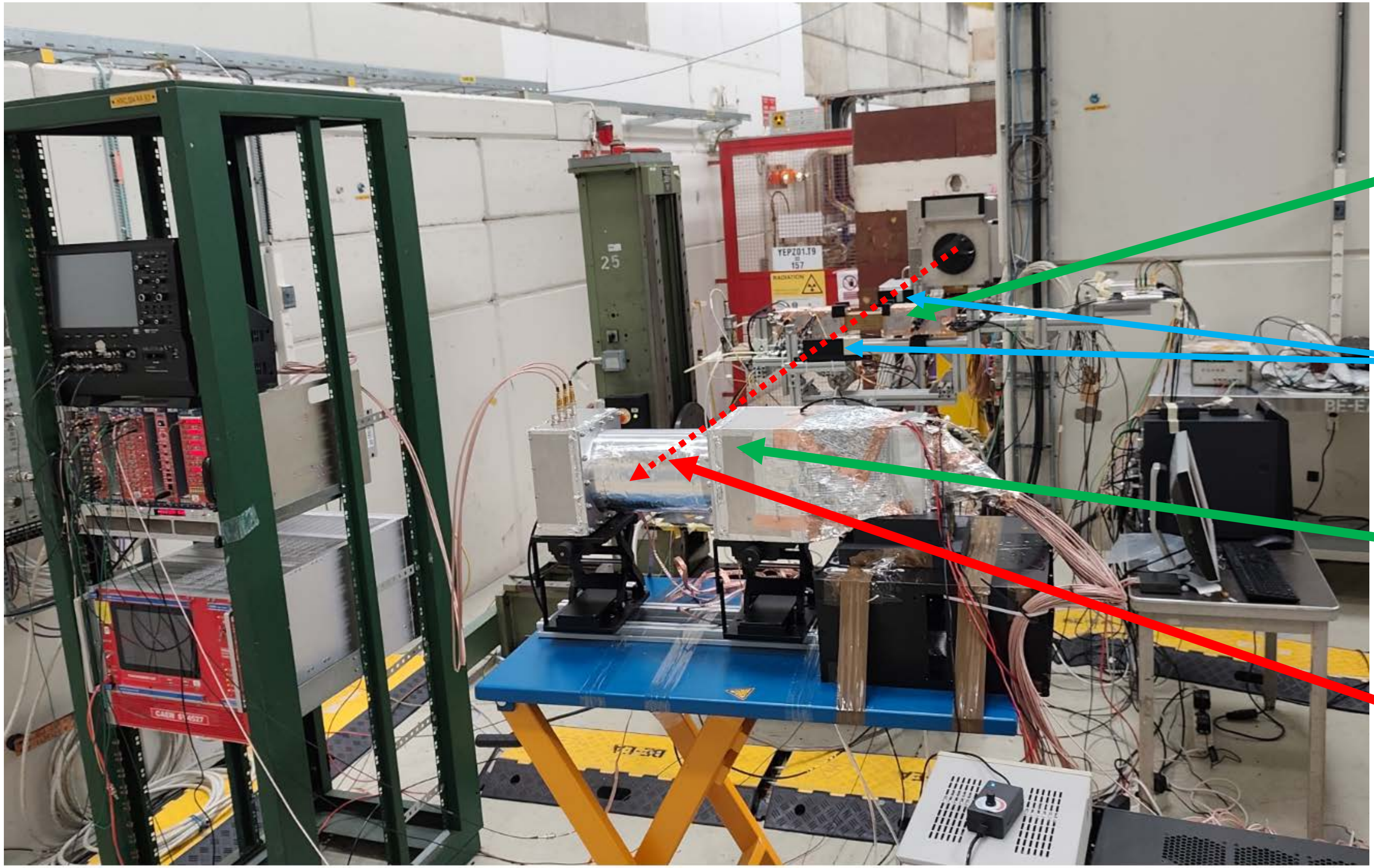
Drift chamber prototype:

- 10 layers, 6 cells/layer, 60 cells
- Cell size: 12 mm × 12 mm
- Length of protopype: 530 mm
- Sense wire: 20 μm Au-plated tungsten
- Field wire: 70 μm Aluminum
- Length of wire: 250 mm

Shared gas mixture and distribution system, shared trigger signal, different readout electronics

Collected data for muon in the momentum range 2-12 GeV, negative pions (95% pure) and kaons in the momentum range 6-15 GeV

Layout of the whole test



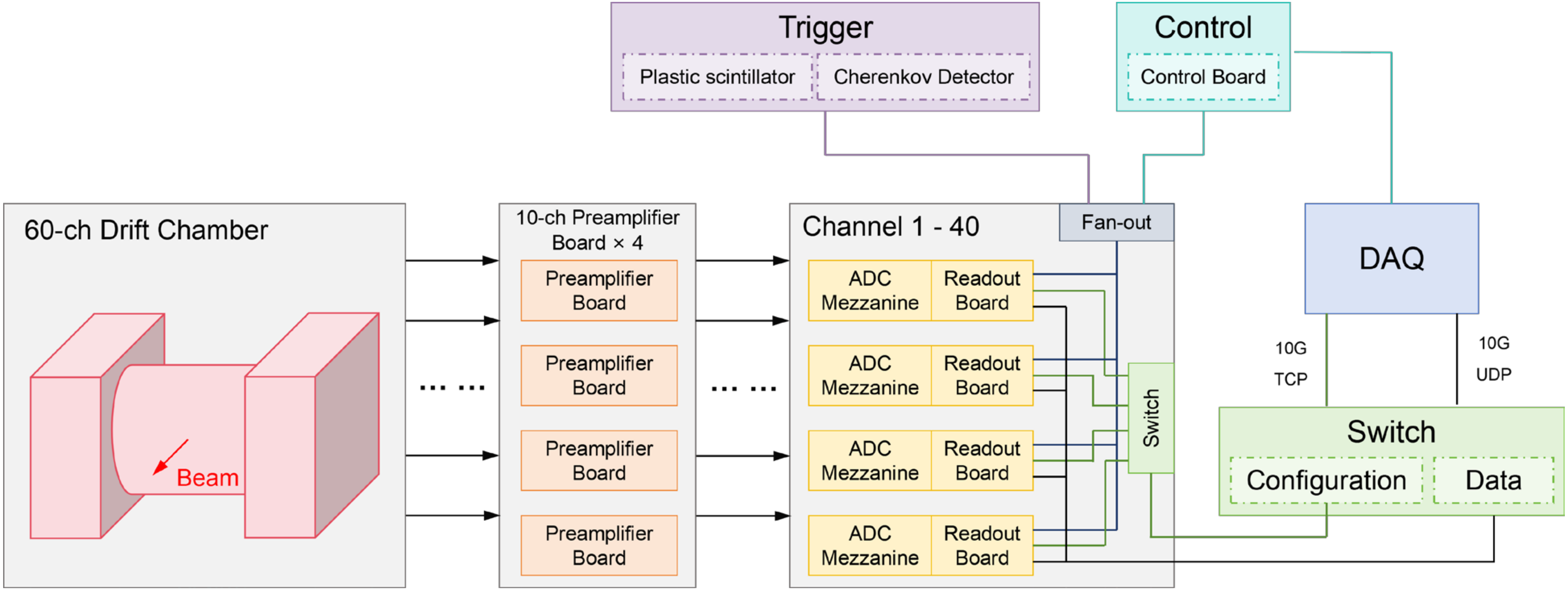
IDEA prototype

Plastic scintillators

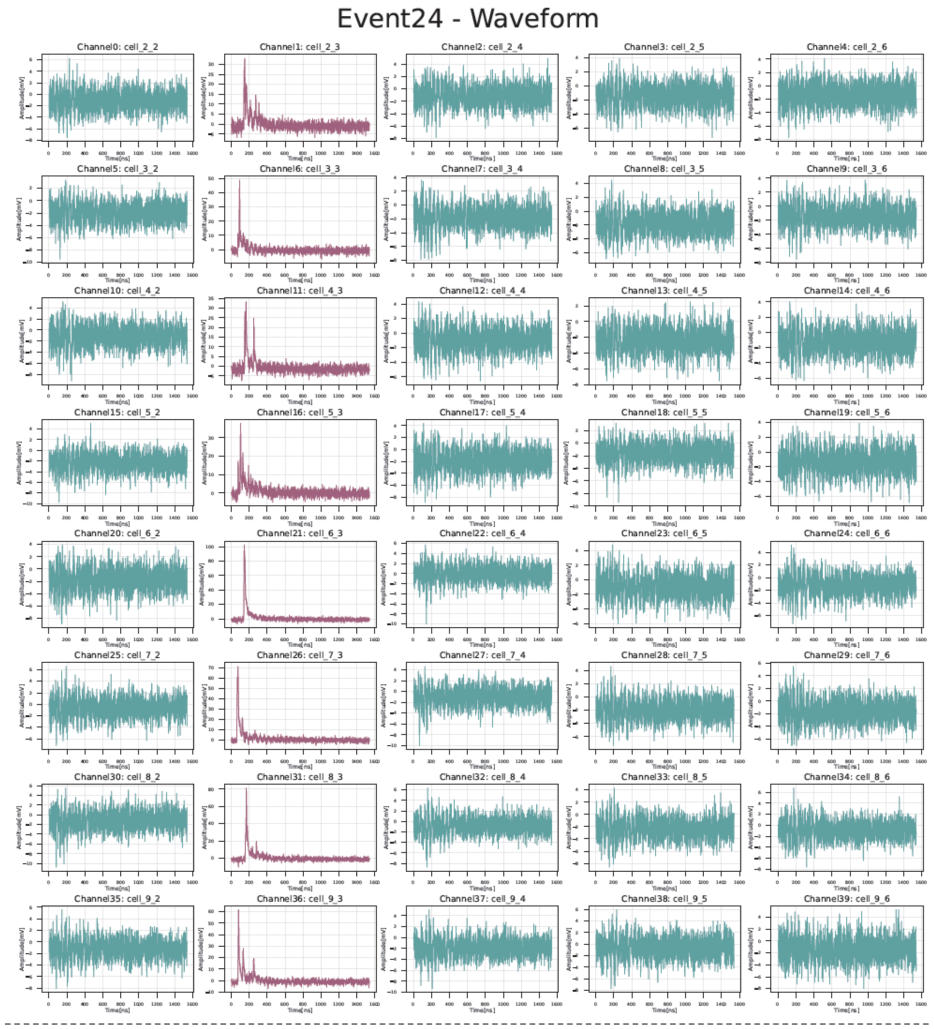
IHEP prototype

Beam

Schematic diagram of the test system

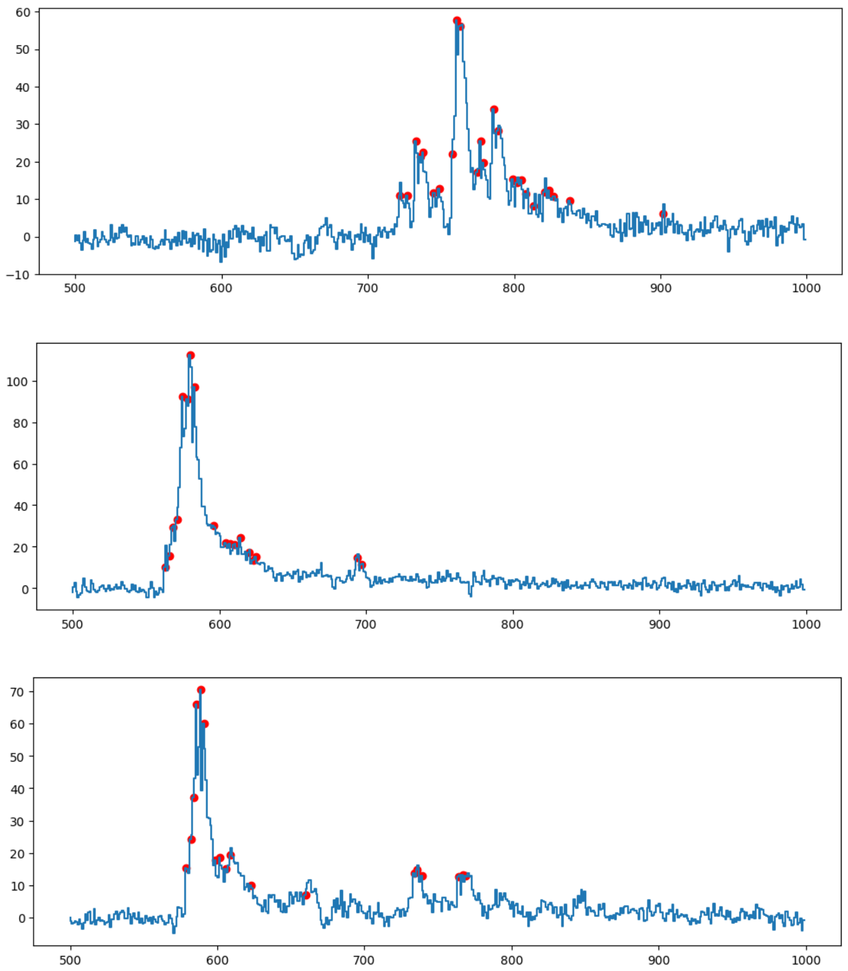


Waveforms and peak-finding



A kaon event with a series of activated cells

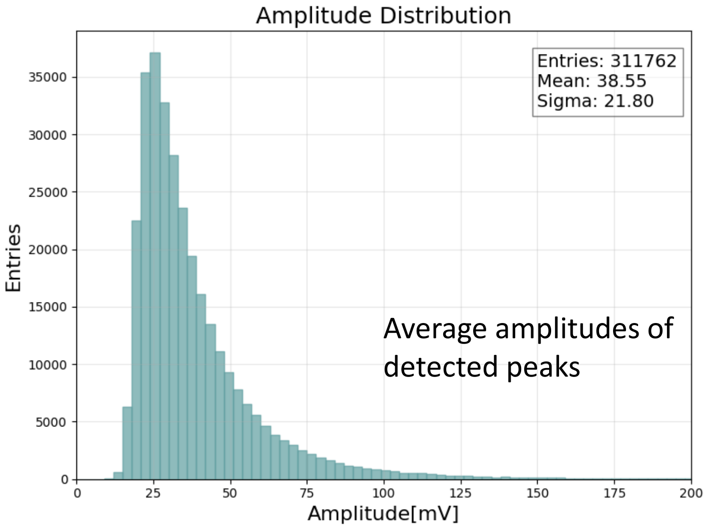
2^{nd} derivative-based peak-finding

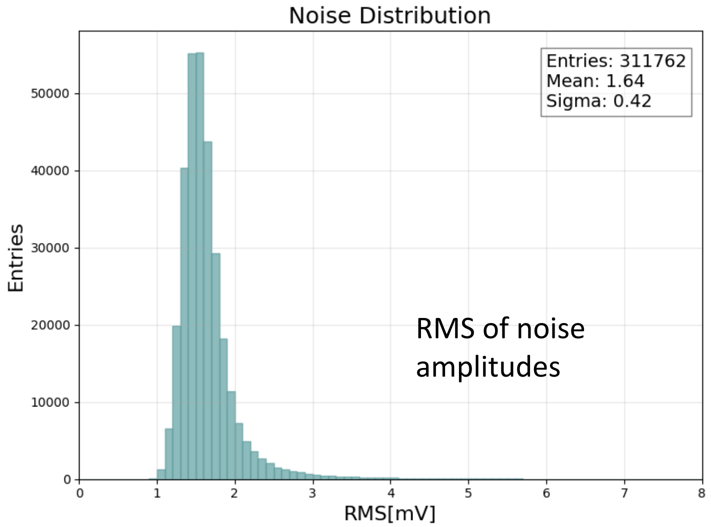


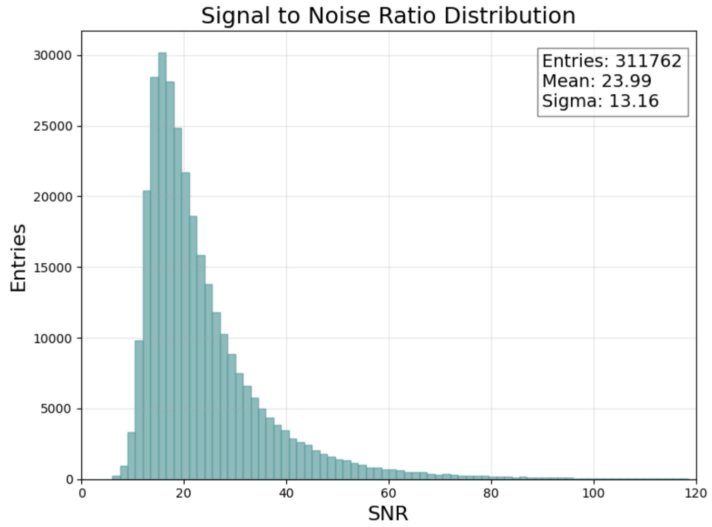
Peak-finding is challenging with noise contaminations and space charge effects

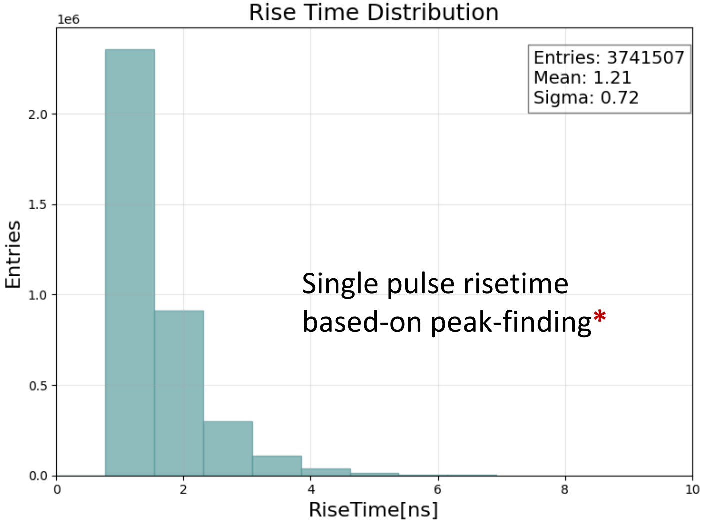
Waveform characterization

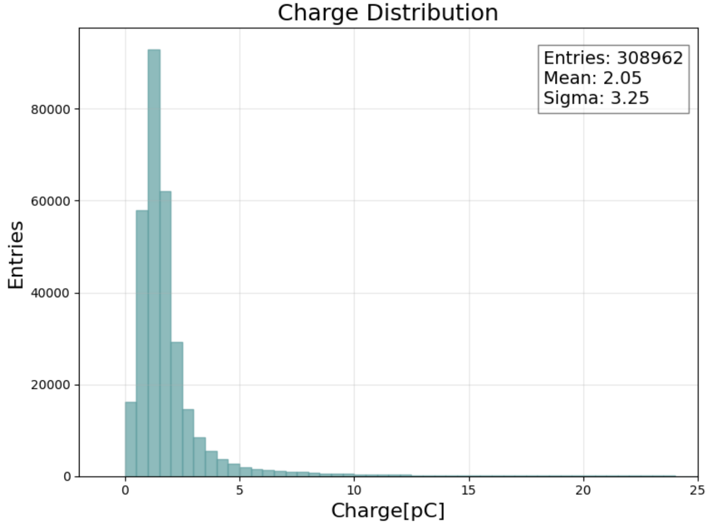
Kaon 10GeV He:iC_4H_{10}=9:1 1725V/1775V







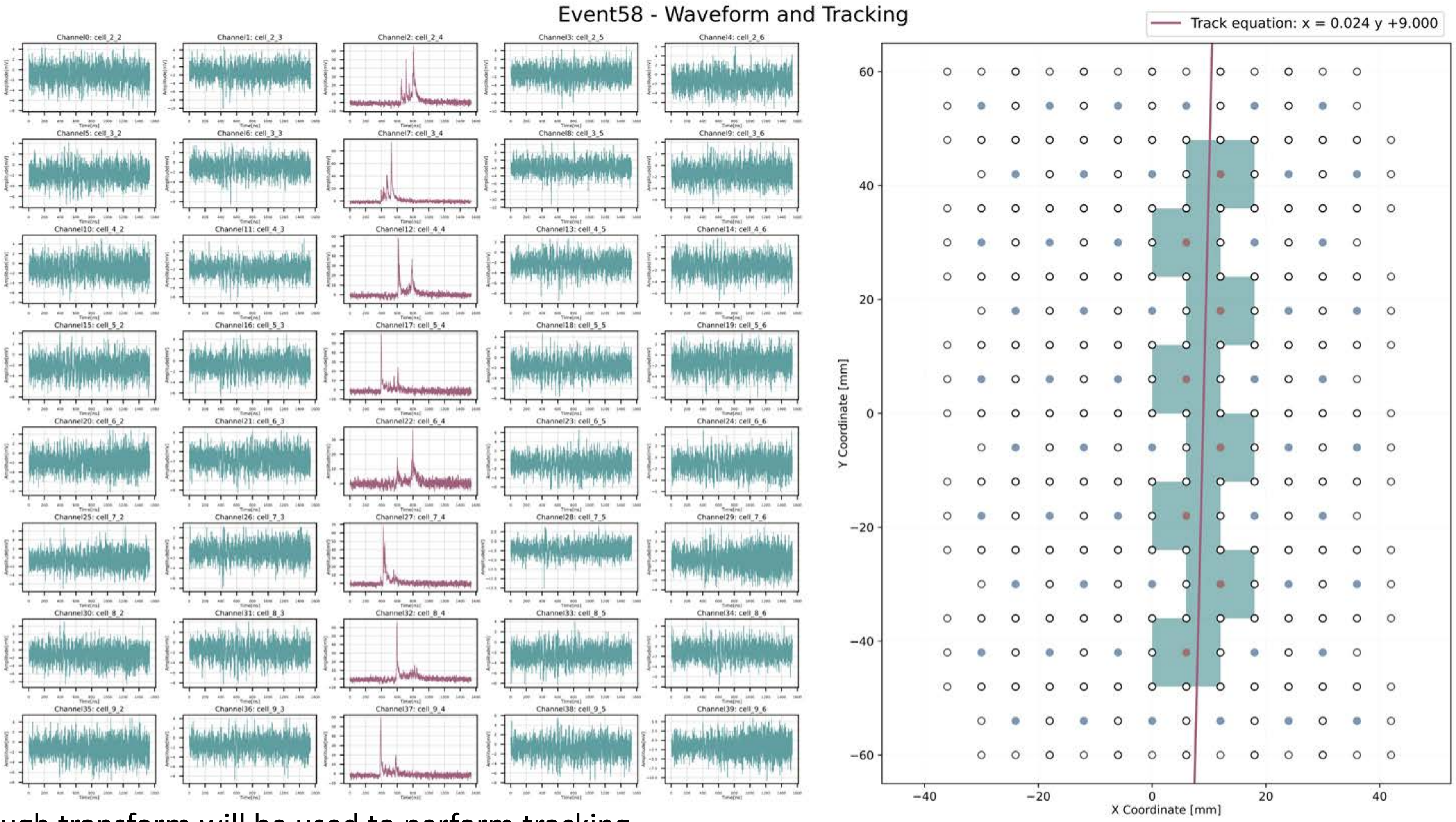




- Amplitude： 38.55 mV
- Noise RMS： 1.64 mV
- SNR： 23.99
- Risetime: 1.21 ns
- Charge： 2.05 pC

Preliminary tracking study

Kaon 10GeV He:iC_4H_{10}=9:1 1725V/1775V



- The Hough transform will be used to perform tracking
- The (k, b) with the highest vote value in Hough space is the track parameters. They will be used as initial values for fitting

Future R&D Challenges of DC

- Study on Aging of New-Type Drift Chamber
  - Drift cells with reduced cell size to withstand high counting rates
  - High electric field
  - High gain required for primary ionization readout
- Low material budget design for large-volume detector; innovative structural design, novel wire material — alloy-metallized carbon wires
  - Wire corrosion, coating quality, etc.
- Hydrocarbon-free gas mixture as working gas
- Achieve high-precision spatial resolution (at the 100 μm level) while enhancing PID capability; characterization of dN/dx performance
  - High-speed electronics
  - Impact of input capacitance (driven by wire length)
  - Data Processing
  - Reconstruction algorithms
- Specific construction techniques for Long/Large Drift Chambers : wire stretching, precise positioning, gas sealing and other processes

Summary

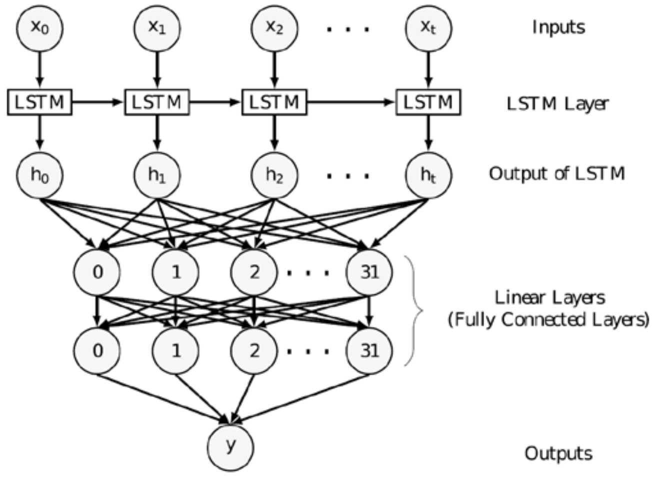
- Drifter chambers have been widely adopted and played irreplaceable roles in past and ongoing high-energy physics experiments.
- With the advancement of new technologies, methodologies and materials, drift chambers remain indispensable tracking detector candidates for next-generation high-energy physics experiments.
- Targeting future high-energy physics experiments, the key development directions and technologies are outlined as follows:
  - Boost performance of track reconstruction and PID
  - Novel technologies and methods (dN/dx measurement)
  - Low material budget: develop advanced materials (carbon wires); optimize wire stringing techniques; design ultra-lightweight structures to suppress multiple Coulomb scattering

Thanks for your attention !

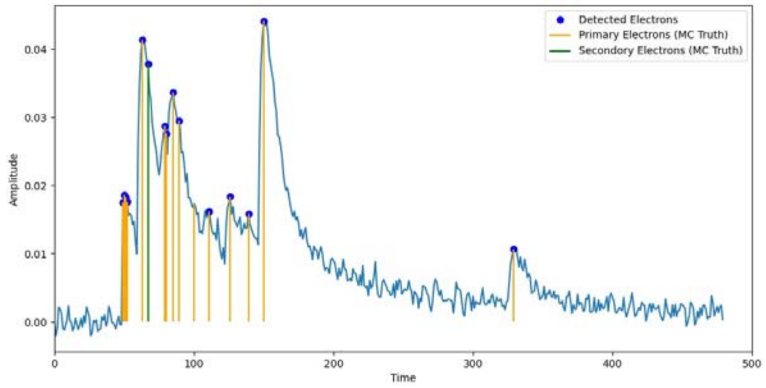
Reconstruction with Deep Learning

- Two DL models have been developed:
  - Simulated samples ([Nucl. Sci. Tech. 36, 113])
    - Supervised model: LSTM peak-finding + DGCNN clusterization
  - Test beam samples ([Comp. Phys. Comm. 300, 109208])
    - Simi-supervised domain adaptation: DNN + Optimal Transport
- Collaboration with INFN group on test beam analysis
  - MC fine tuning to match real data
  - Trained LSTM + CNN with MC, and apply on test beam 2022 data

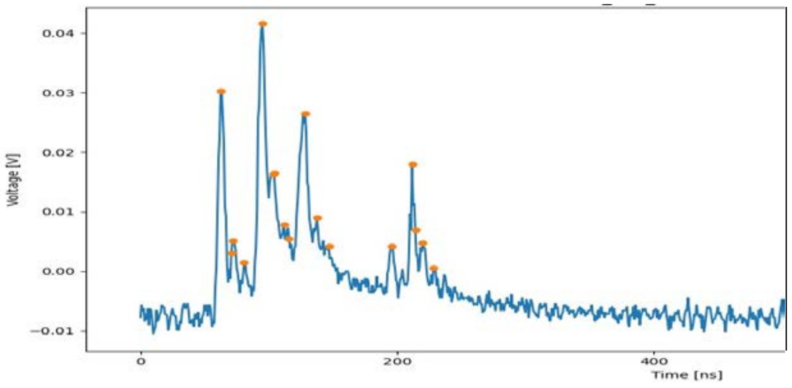
LSTM Peak-Finding Model



Tuned MC Waveform



Read Data Waveform



# of Clusters in Data