Drift chamber with cluster counting technique for CEPC

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On behalf of CEPC drift chamber group

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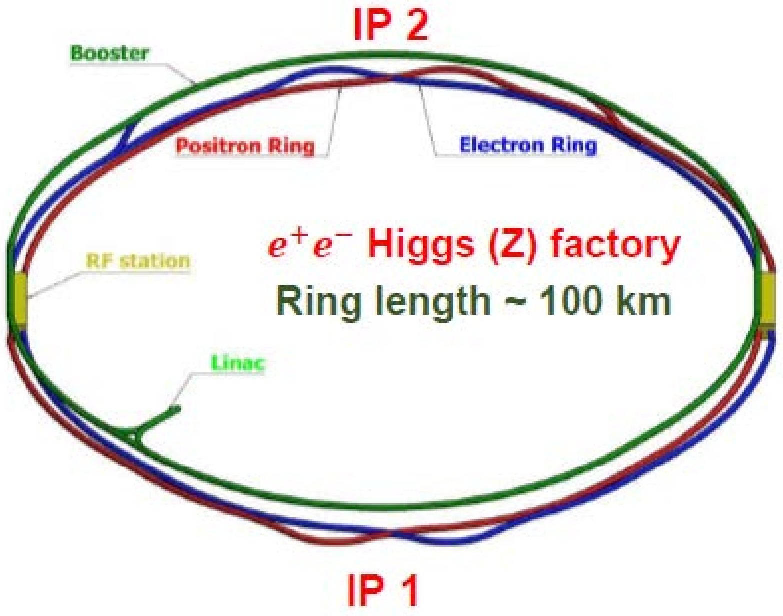
Outline

- Introduction of drift chamber with dN/dx technique
- Performance study and prototype tests
- Preliminary mechanical design and FEA
- Overall scheme for electronics
- Summary

The Circular Electron Positron Collider

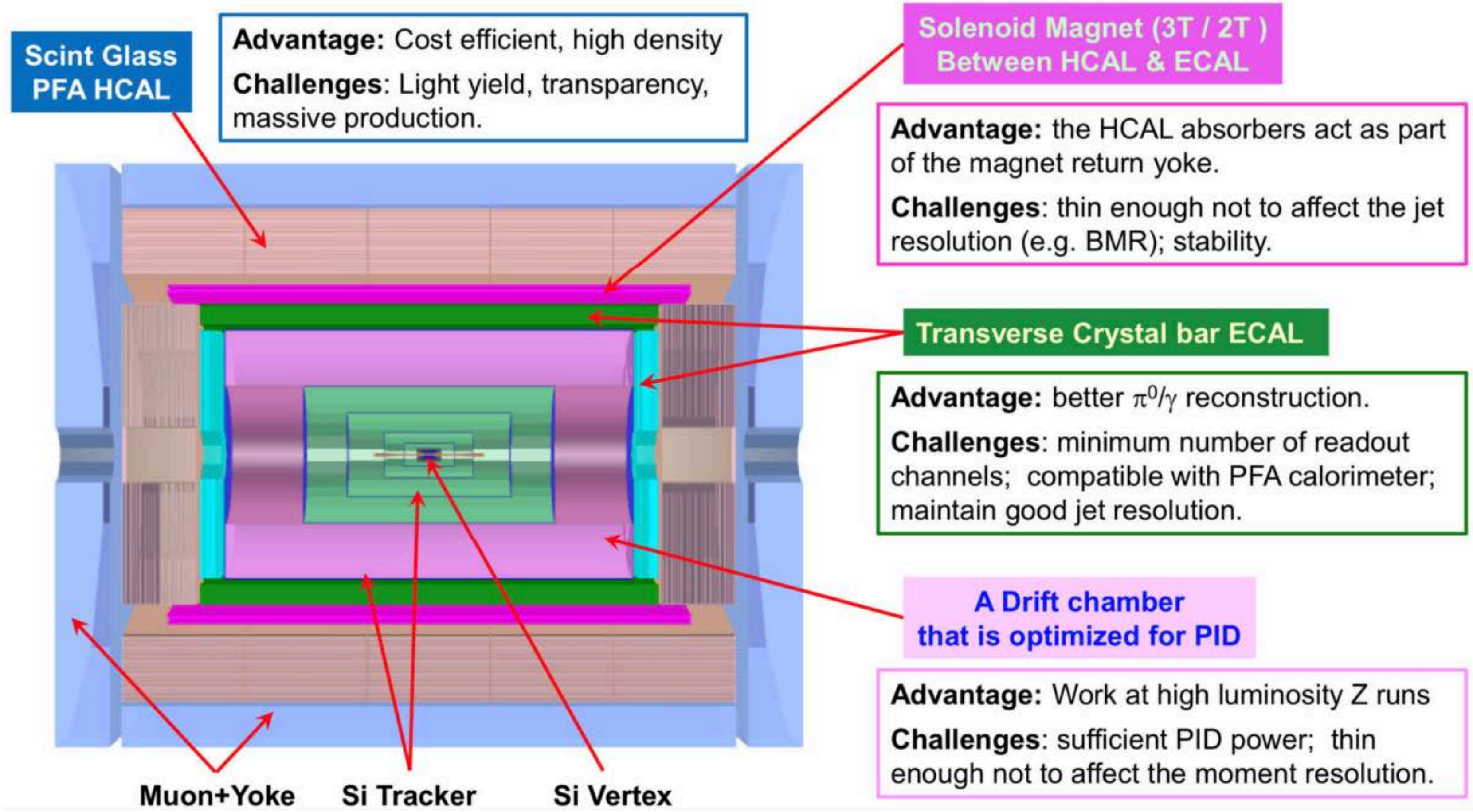
- The CEPC was proposed in 2012 after the Higgs discovery. It aims as an e^+e^- Higgs / Z Factory.
- To produce Higgs / W / Z / top for high precision Higgs, EW measurements, studies of flavor physics & QCD, and probes of physics BSM.
- It is possible to upgrade to a $\boldsymbol{pp}$ collider (SppC) of $\sqrt{s}$ ~ 100 TeV in the future.



Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP (10^{34}cm^{-2}s^{-1})	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.
** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.
*** Calculated using 3,600 hours per year for data collection.

Drift Chamber in CEPC 4th conceptual detector

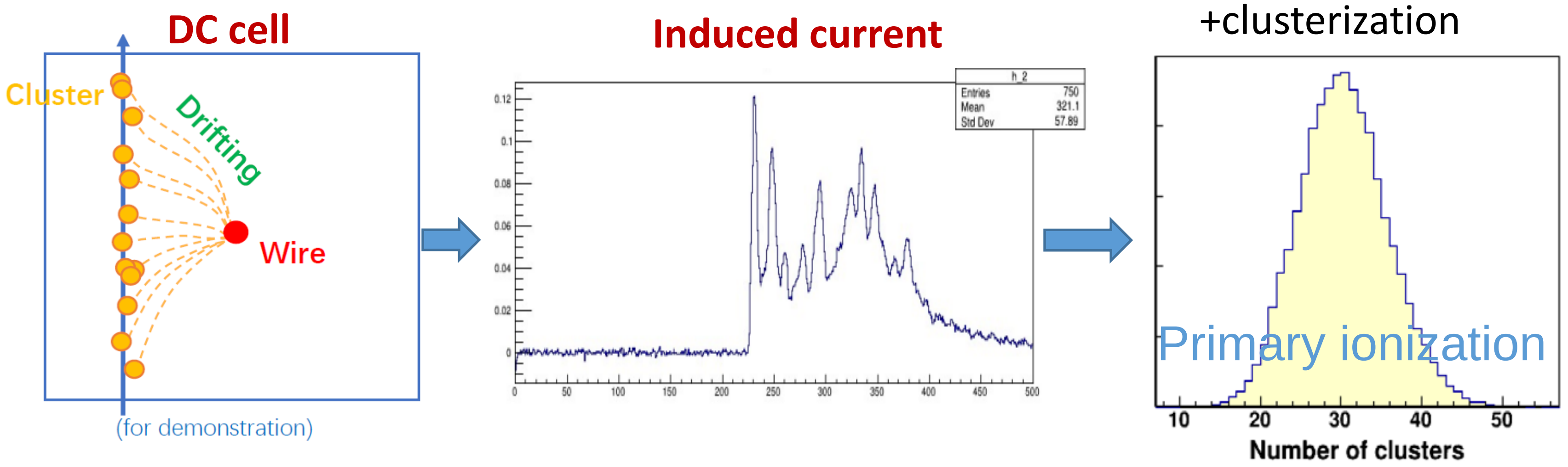


PID is essential for CEPC, especially for flavor physics

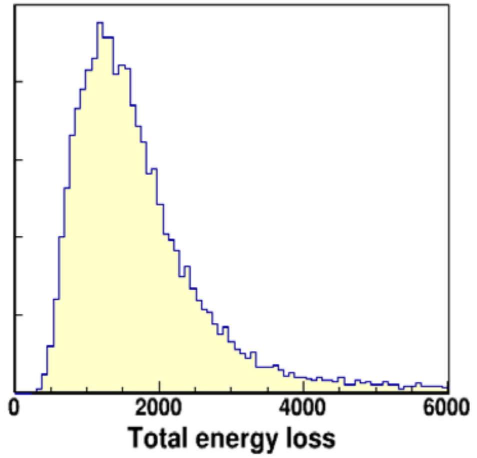
- A drift chamber between the two outer layers of Si tracker, optimized for its PID power
- Require better than 3σ separation power for K/π with momentum up to 20GeV/c
- Benefits tracking and momentum measurement

Ionization measurement with dN/dX

dN/dx



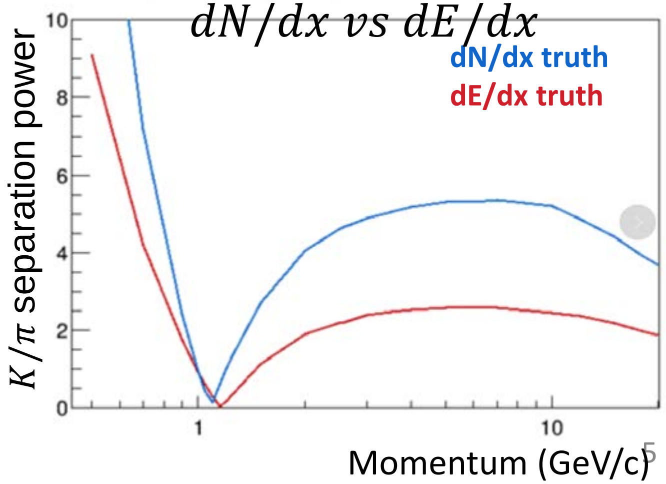
dE/dx



- dN/dx: Measure number of clusters over the track, which corresponds to the number of the primary ionization
- Yield of primary ionization is Poisson distribution
- Small fluctuation
- dN/dx has a much better (2 times) K/π separation power up to 20 GeV/c compared to dE/dx (Simulation)

K/π separation power

dN/dx vs dE/dx



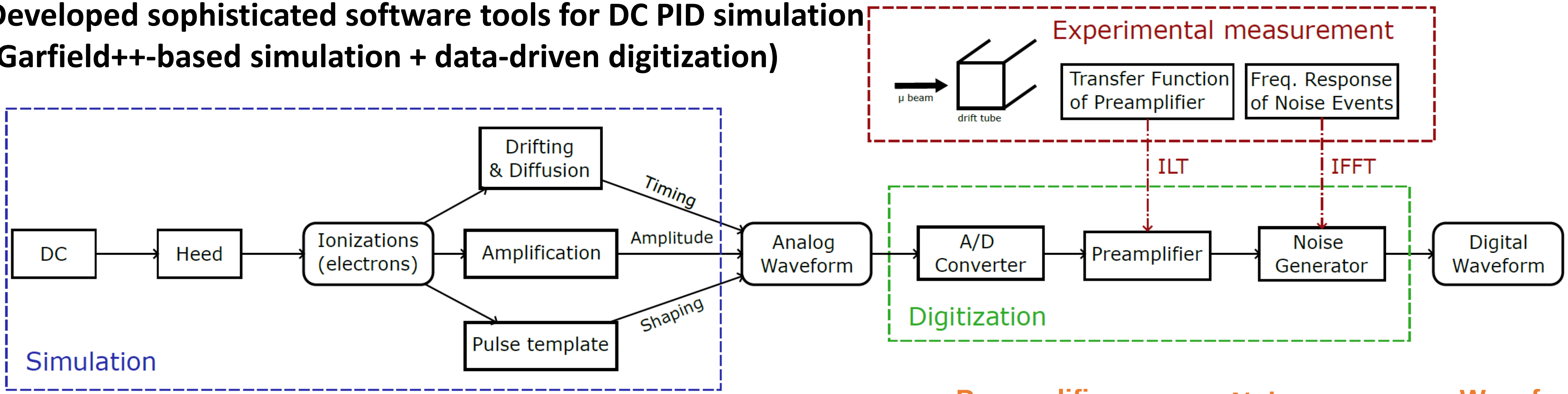
Key issues with dN/dx measurement

- Detector optimization and performance study
  - dN/dx resolution and PID capability
  - Geometry of the detector
  - Mechanical structure, Material budget
  - Gas mixture: low drift velocity, suitable ionization density gas with low diffusion and low multi electron ionization
- Waveform test
  - Fast and low noise electronics
- dN/dx reconstruction algorithm
  - Identifying primary and secondary ionization signals
  - Reducing noise impacts
  - Improve the reconstruction efficiency

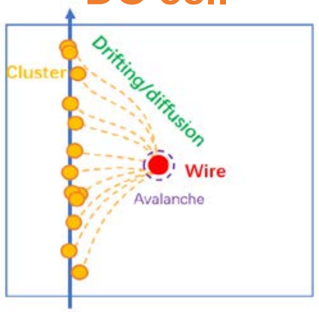
Performance study and Detector R&D

Waveform-based full simulation

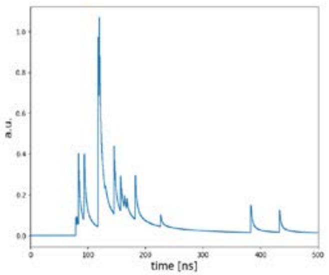
Developed sophisticated software tools for DC PID simulation (Garfield++-based simulation + data-driven digitization)



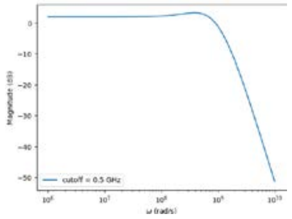
DC cell



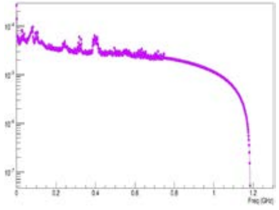
Induced signal



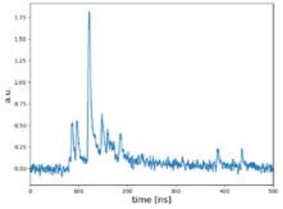
Preamplifier



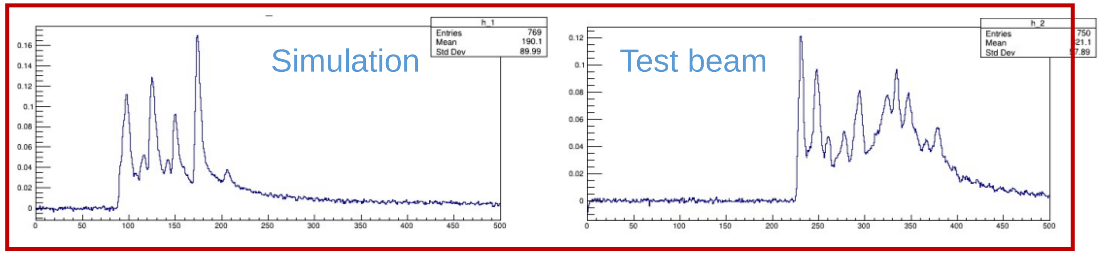
Noise



Waveform



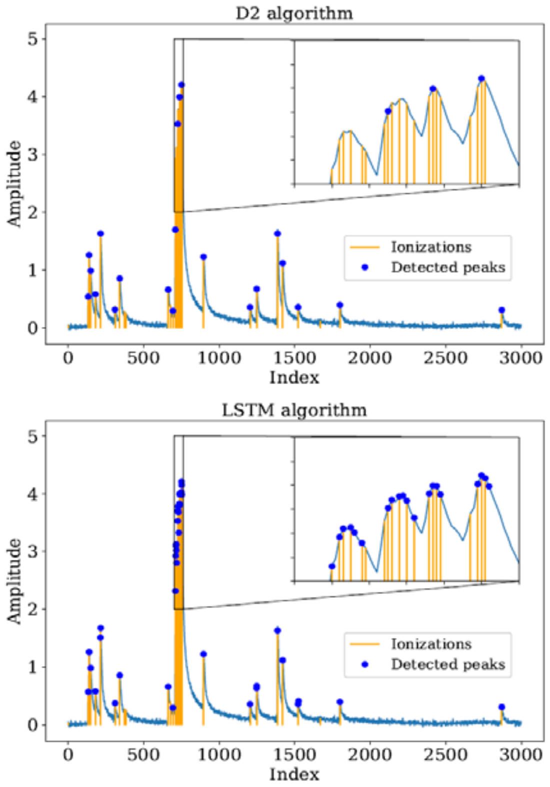
Tuned MC is comparable to data

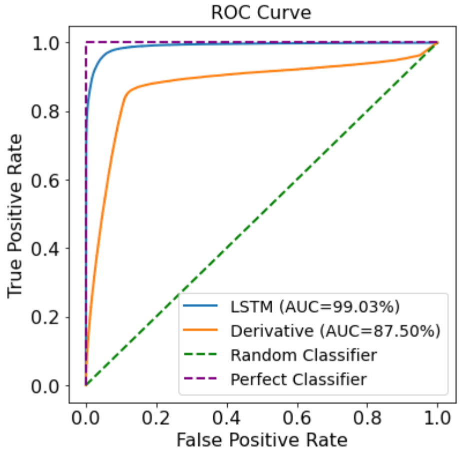


Machine learning reconstruction algorithm

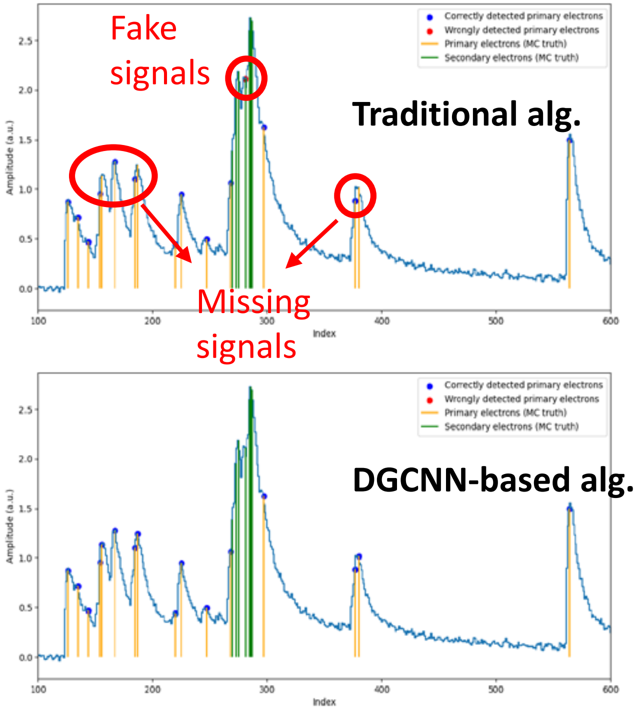
- LSTM-based peak finding and DGCNN-based clusterization
- ~ 10% improvement of PID performance with ML

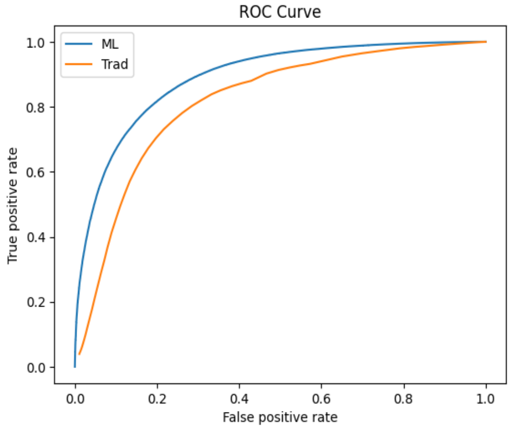
Long Short-Term Memory (LSTM)-based peak finding
higher efficiency than the derivative-based algorithm, especially for the pile-up recovery





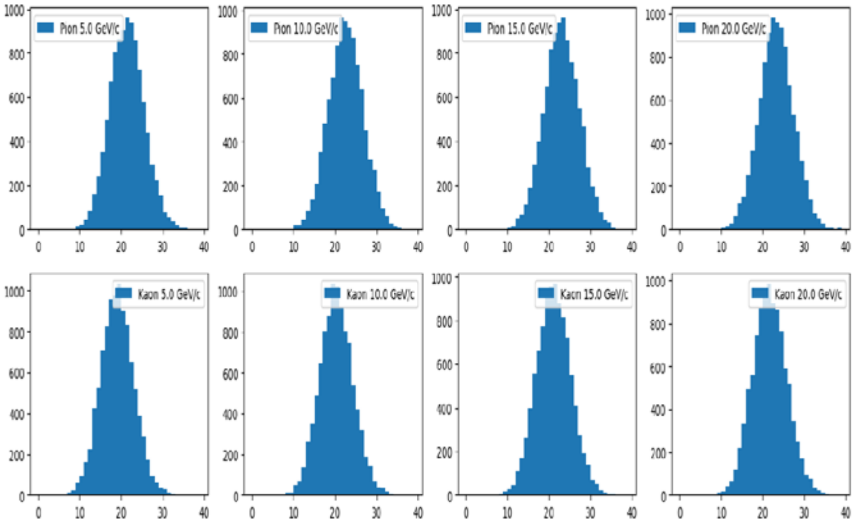
Dynamic Graph CNN (DGCNN)-based clusterization
higher efficiency, and lower fake rate



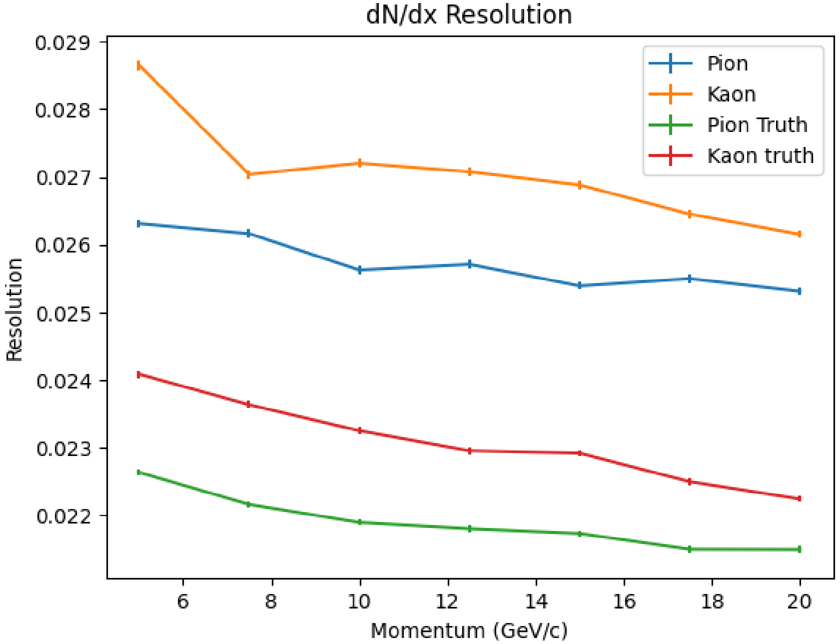


dN/dx Resolution

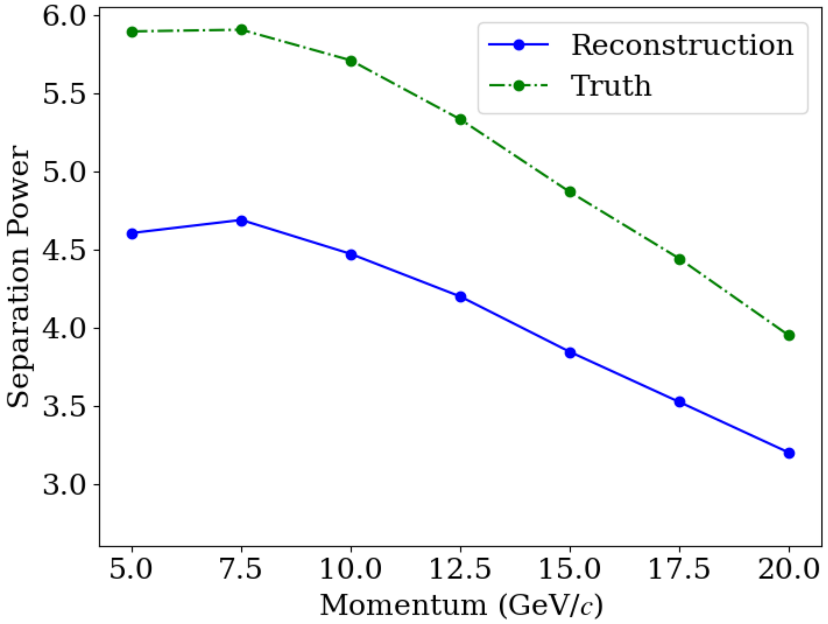
Reconstructed # of clusters distributions



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

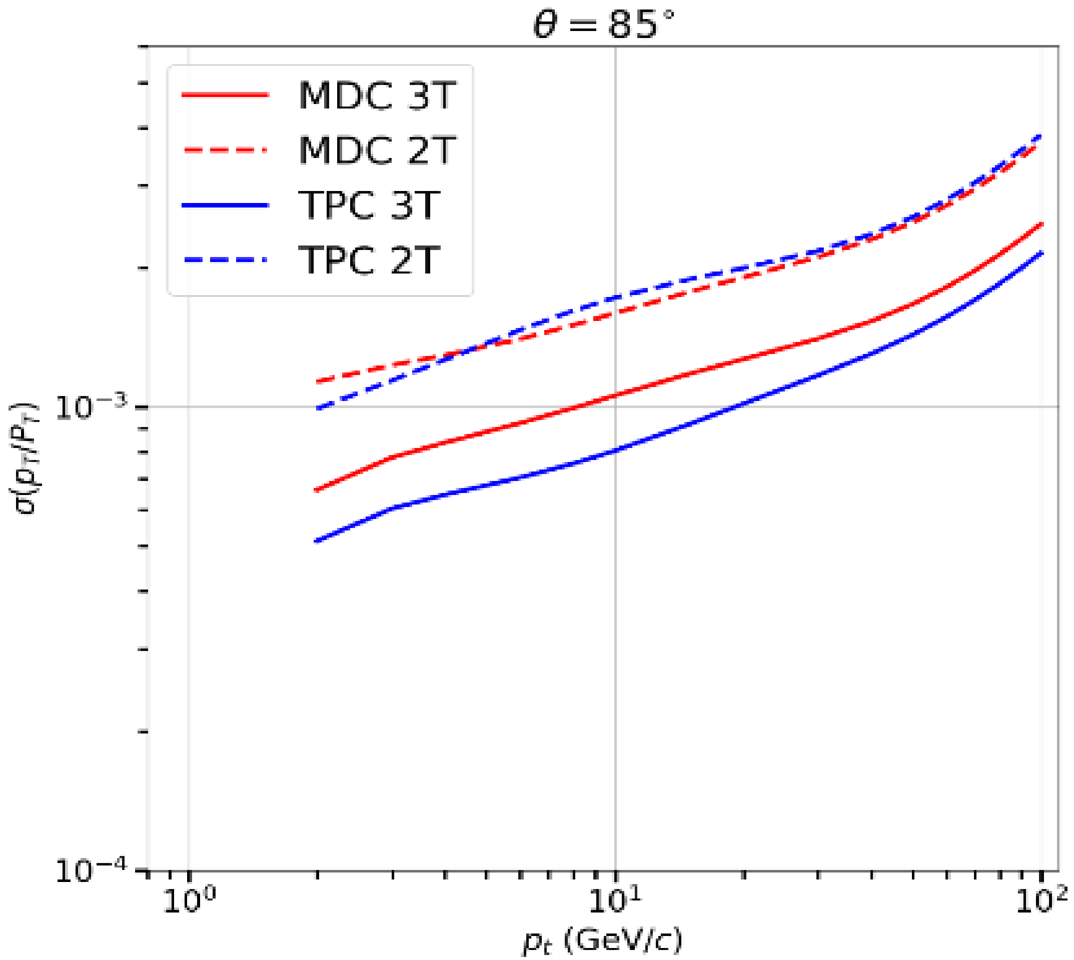


- dN/dx resolution (1.2 m track length):
  - 2.5%-2.6% for Pion
  - 2.6%-2.7% for Kaon



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

Momentum Resolution

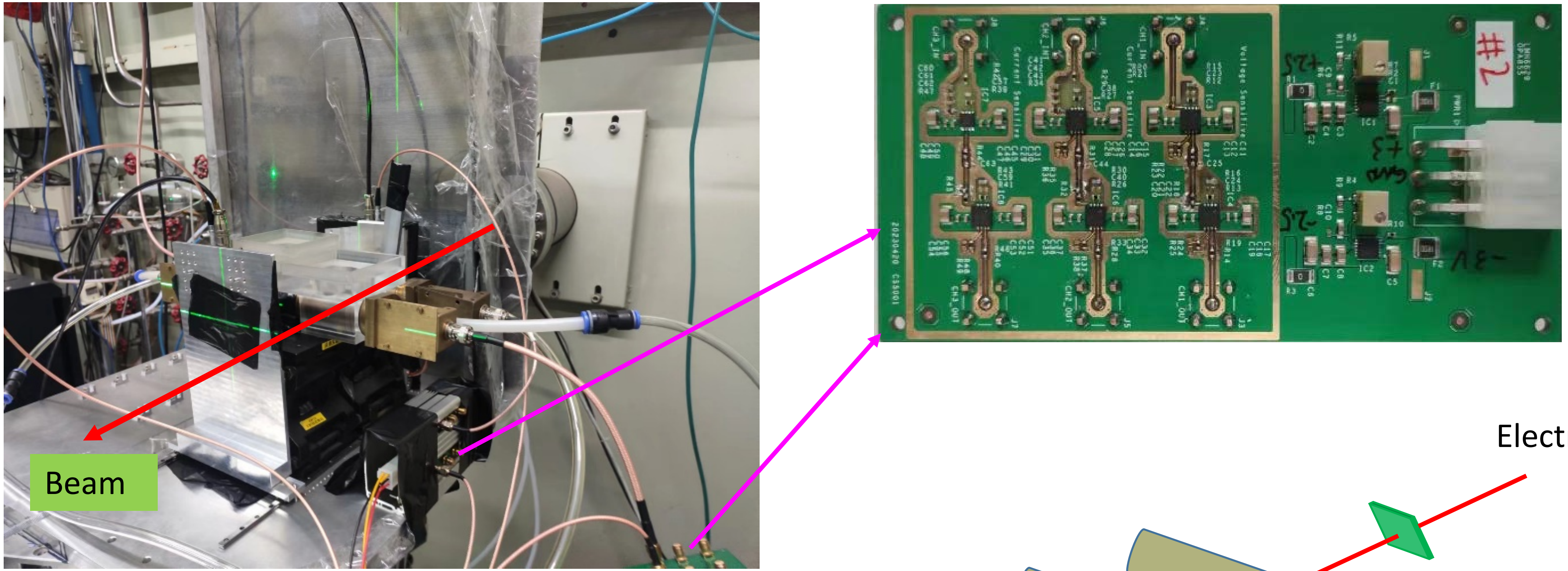


$\sigma(1/p_t) = a \pm b/p_t$

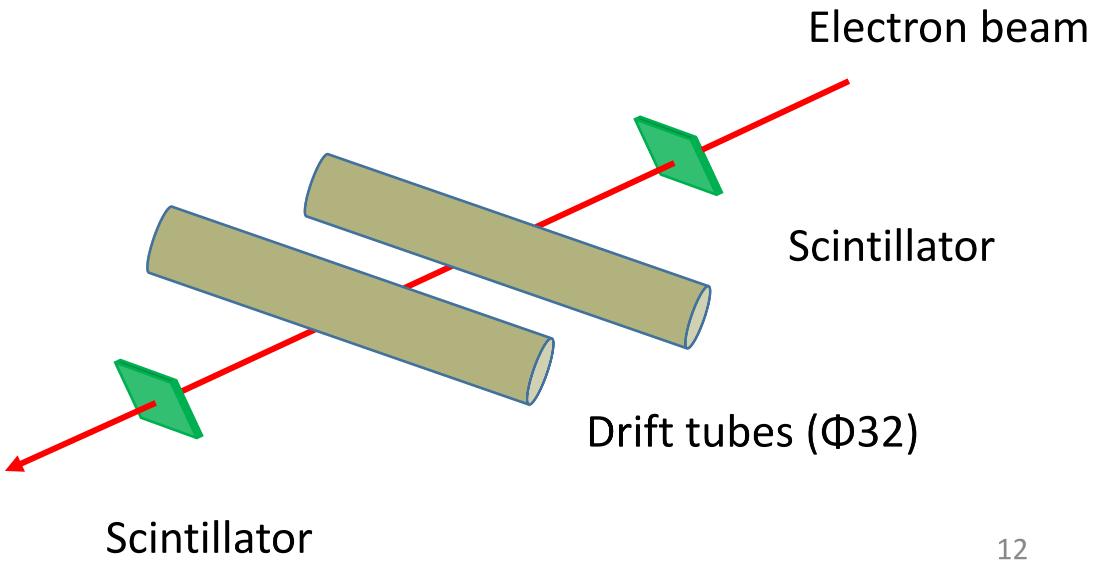
	Higgs	Z-pole
a (1/GeV)	2.1×10^{-5}	3.2×10^{-5}
b	0.77×10^{-3}	1.16×10^{-3}

Momentum resolution is comparable with TPC at Higgs and Z mode

Detector R&D and beam test

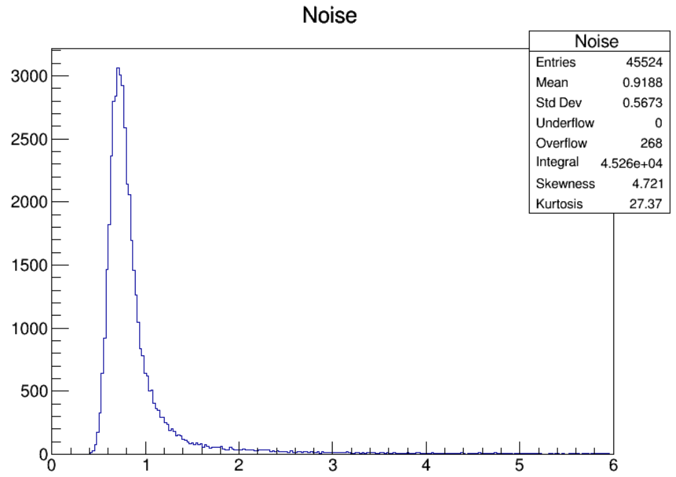


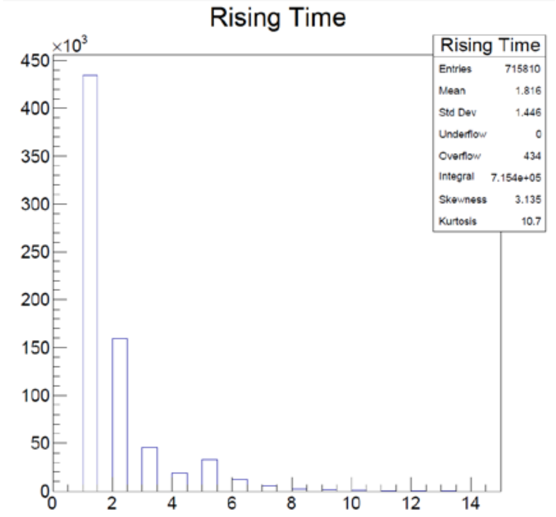
- Developed fast and high bandwidth preamps
- Tested with electron beam at IHEP
  - Two drift tubes + preamps + ADC (1GHz)
  - Two scintillators provide trigger signals

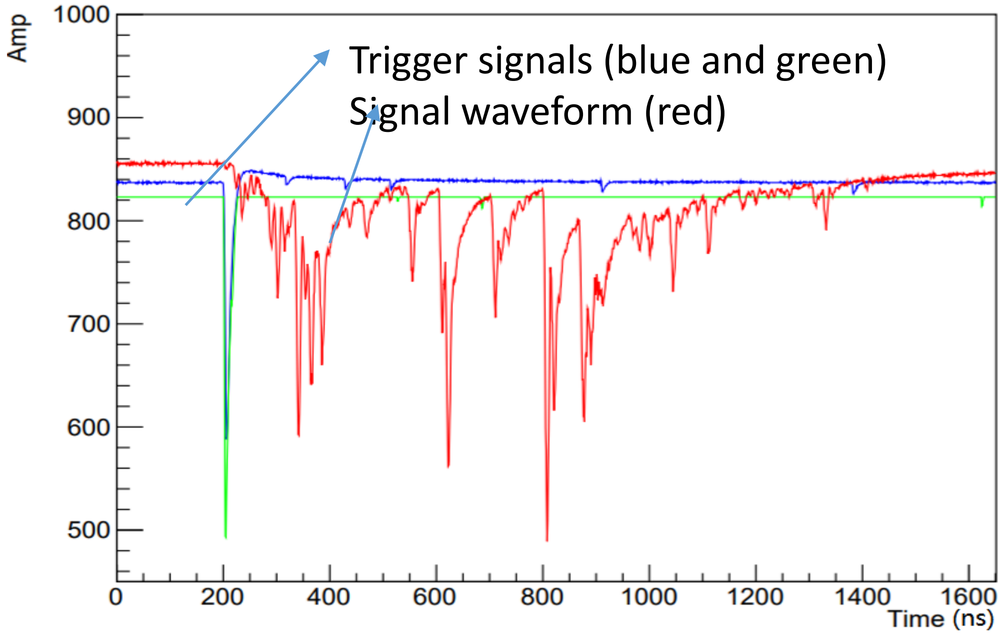


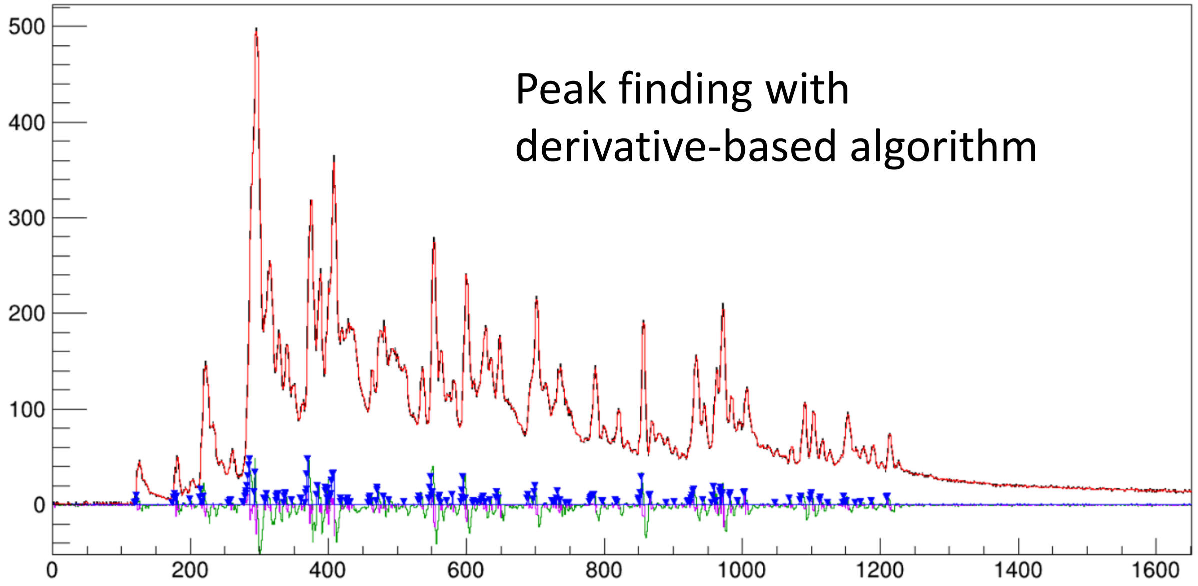
Preliminary results

- Clear peaks
- Rise time : ~ ns
- The performance of preamplifiers:
  - Low noise
  - high bandwidth

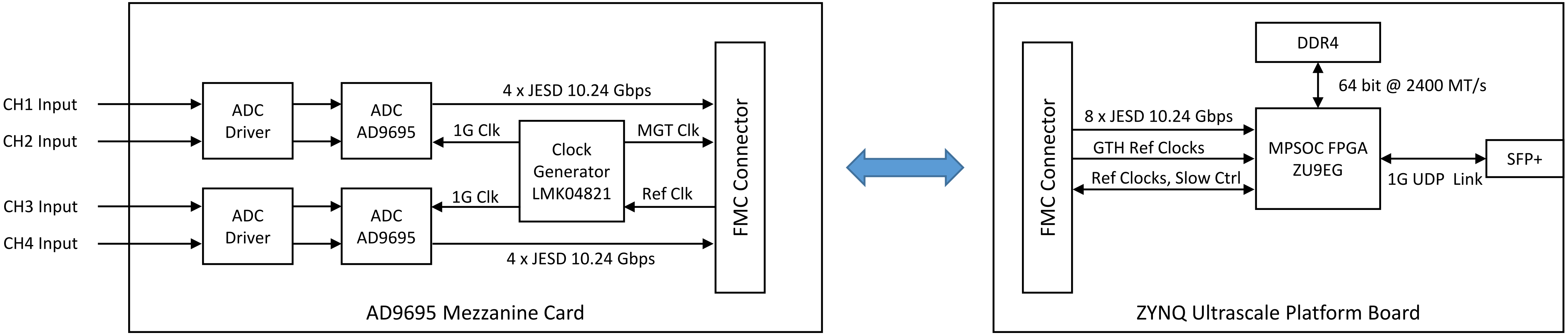


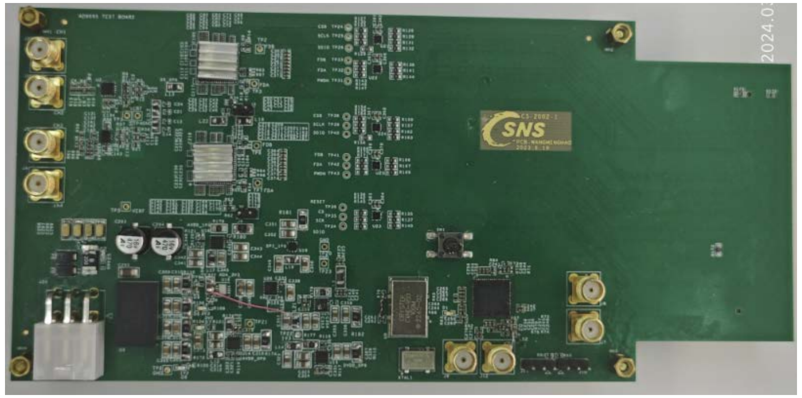


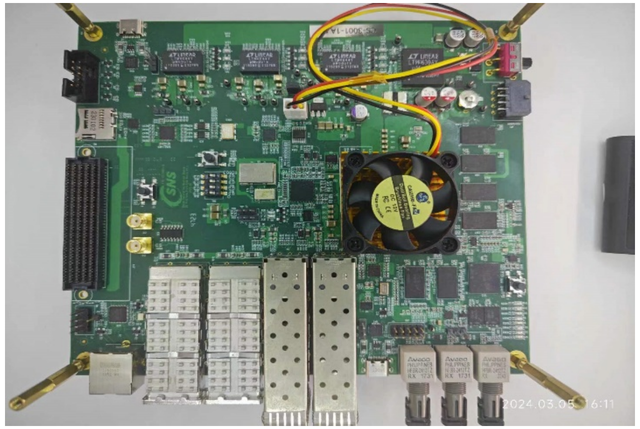




Readout electronics design



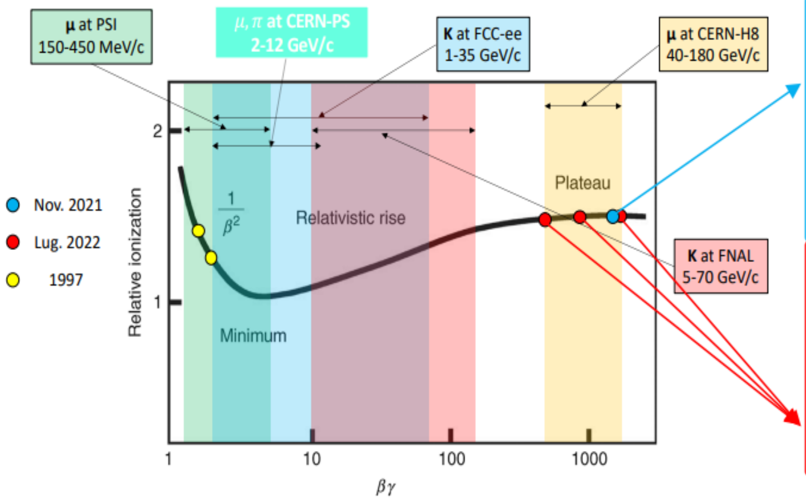


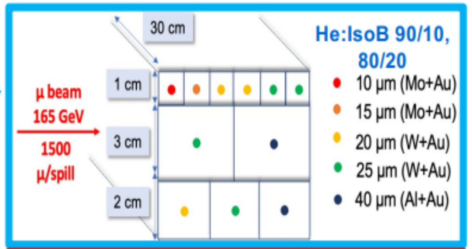


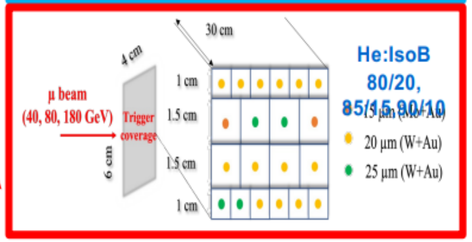
- A readout prototype system is developed to verify basic functions, consisting of an ADC board and an FPGA board. will be integrated into one board in next version
- The ADC board is based on two high-speed ADCs (ADI AD9695), 14 bit resolution, and a maximum sampling of 1.4 Gsps

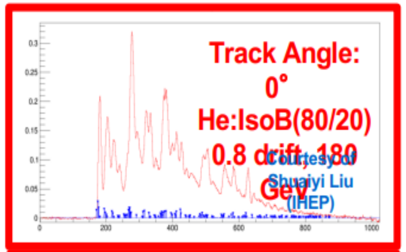
Synergy with IDEA, Collaboration with INFN

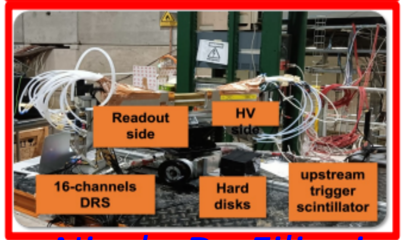
- Beam tests organized by INFN group:
  - Two muon beam tests performed at CERN-H8 ($\beta\gamma > 400$) in Nov. 2021 and July 2022
  - A muon beam test (from 4 to 12 GeV/c) in 2023 performed at CERN
  - Test in 2024 is under going to fully exploit the relativistic rise (starting on July 10).
- Contributions from IHEP group:
  - Participate data taking and collaboratively analyze the test beam data
  - Develop the machine learning reconstruction algorithm

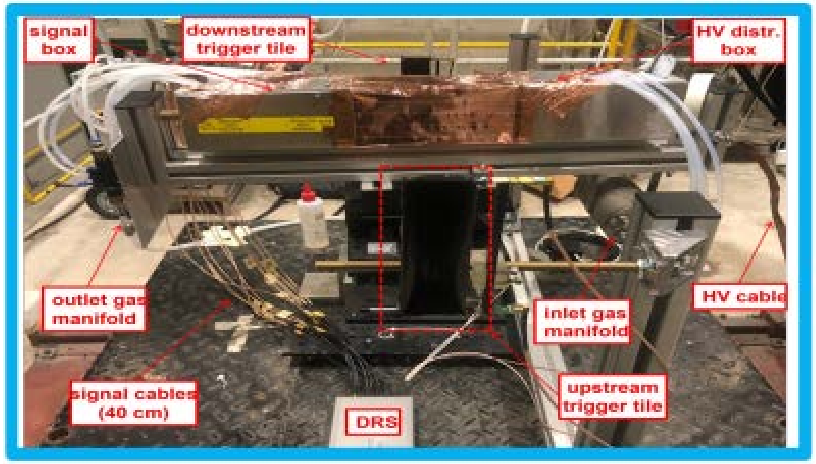








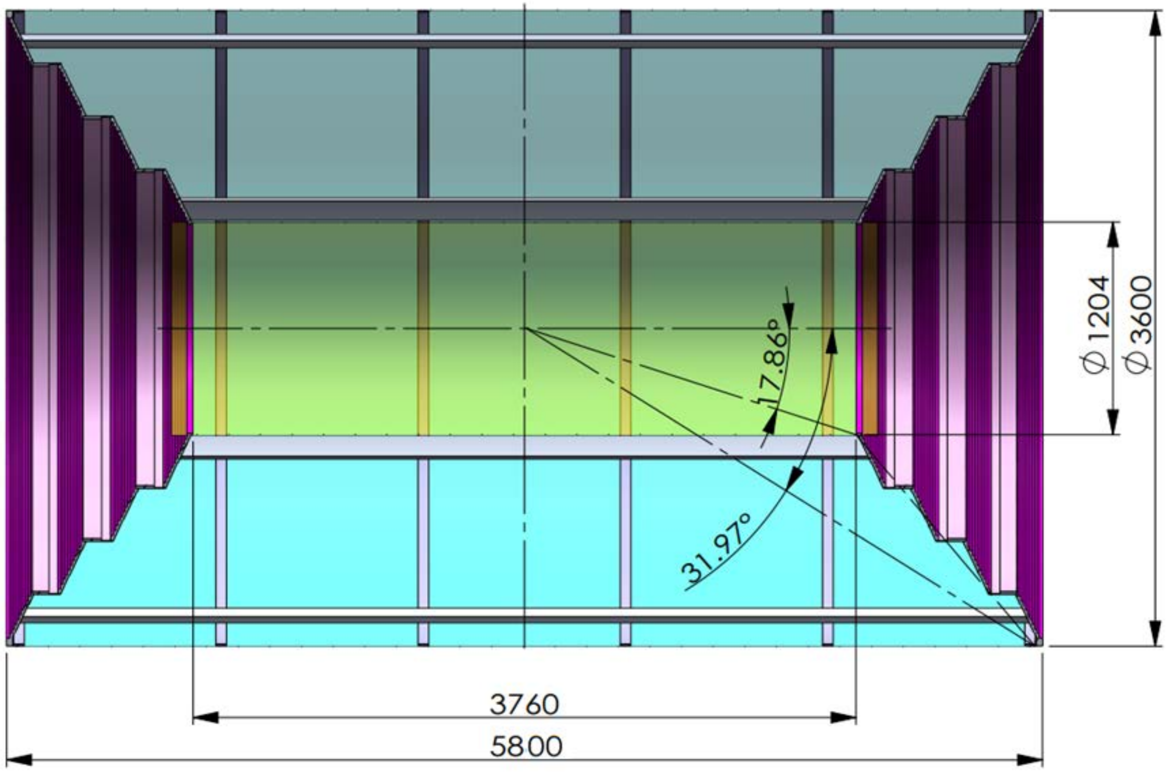




Preliminary design of mechanics and Readout scheme

Overall mechanical design

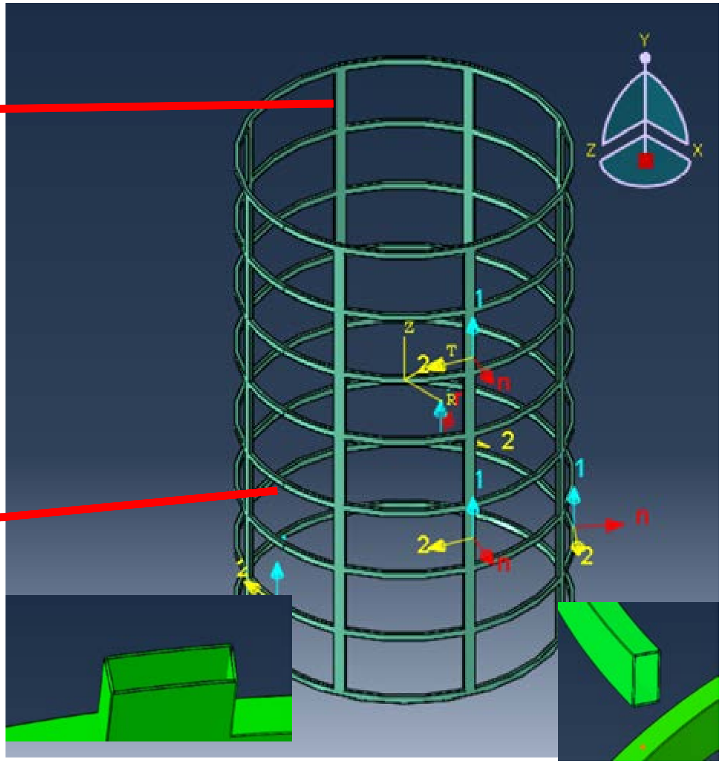
End plates + CF frame structure



CF frame structure

Cross section of longitudinal HB：80mm*40mm，thickness: 3.2mm

Cross section of annular HB：40*10mm Thickness: 3.2mm



- CF frame structure: 8 longitudinal hollow beams + 8 annular hollow beams + inner CF cylinder and outer CF cylinder
  - Length: 5800 mm
  - Inner diameter: 1200 mm, Outer diameter: 3600 mm
- Each End plate: including 4 steps, thickness: 20 mm, weight: 880 kg

Wire tensions

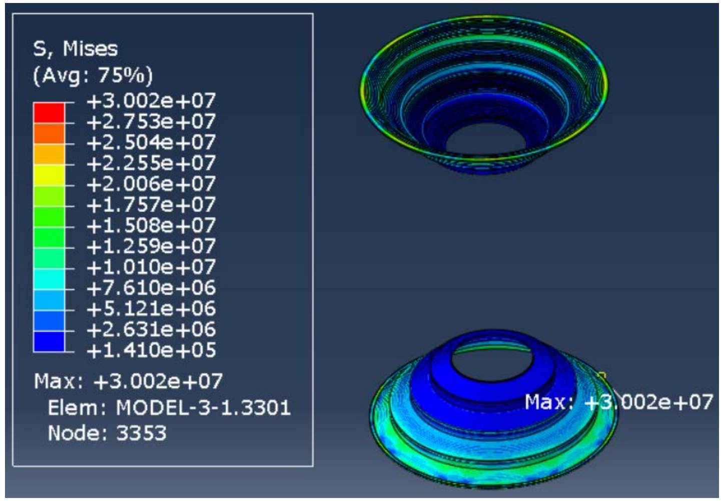
	Cell number/step	Average length (mm)	Single sense wire tension (g)	Single field wire tension (g)	Total tension/step (kg)
step1	9172	5668	86.92	133.56	4472.08
step2	7528	5122	70.98	109.07	2997.38
step3	5845	4526	55.43	85.16	1817.14
step4	3939	3928	41.75	64.14	922.46
total	26483				10209

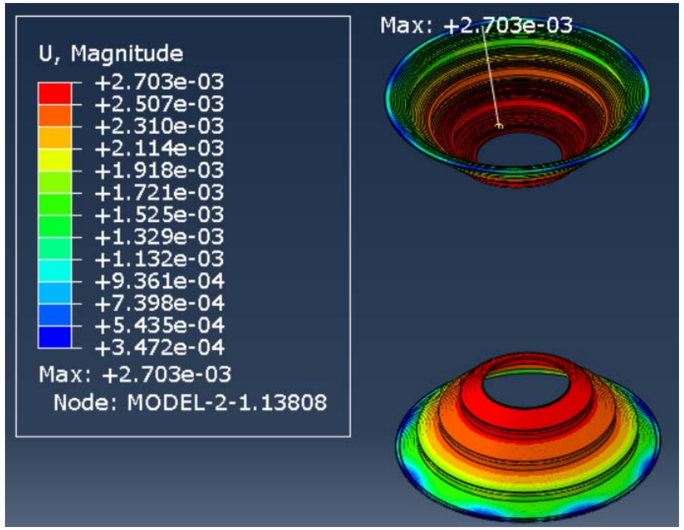
Diameter of field wire (Al coated with Au) : 60μm
Diameter of sense wire (W coated with Au): 20μm
Sag = 280 μm

Meet requirements of stability condition:

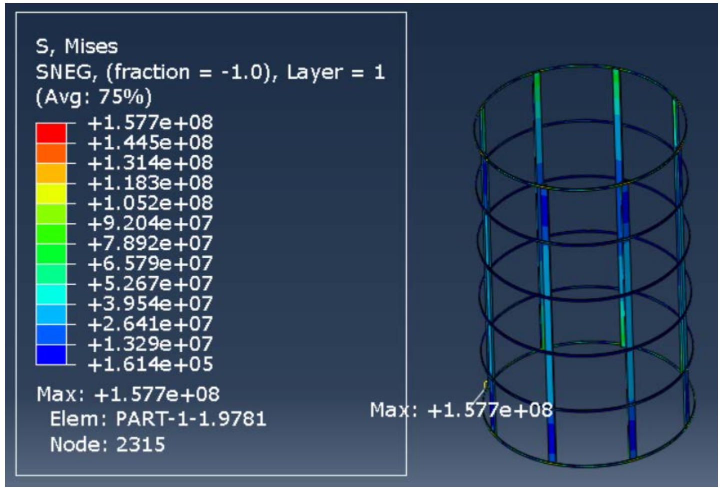
$$T > (\frac{VLC}{d})^2/(4\pi\varepsilon_0)$$

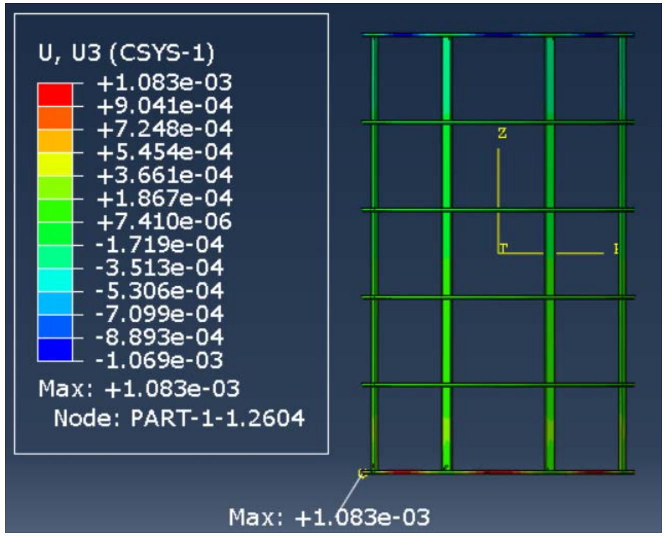
Finite element analysis





- Max Mises tress of End plate : 30MPa
- Endplate deformation 2.7mm





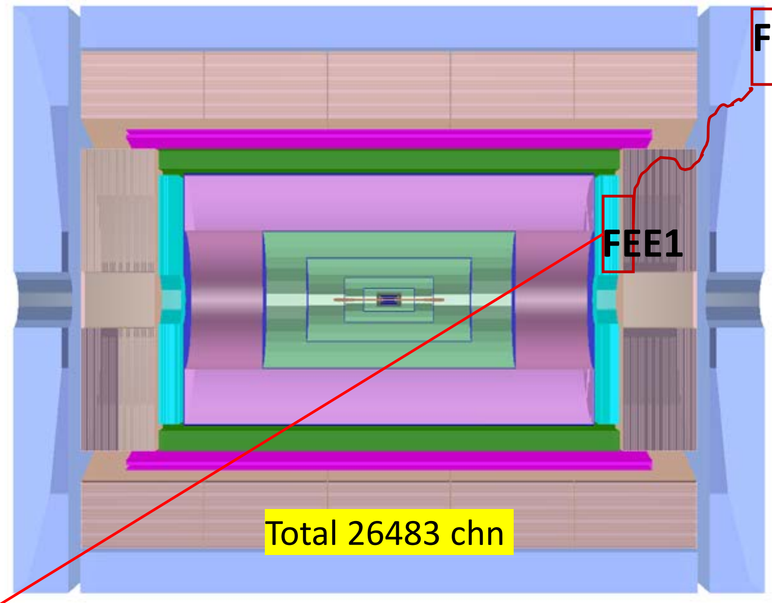
- Max Mises tress of CF frame : 235MPa
- CF frame deformation 1.1mm

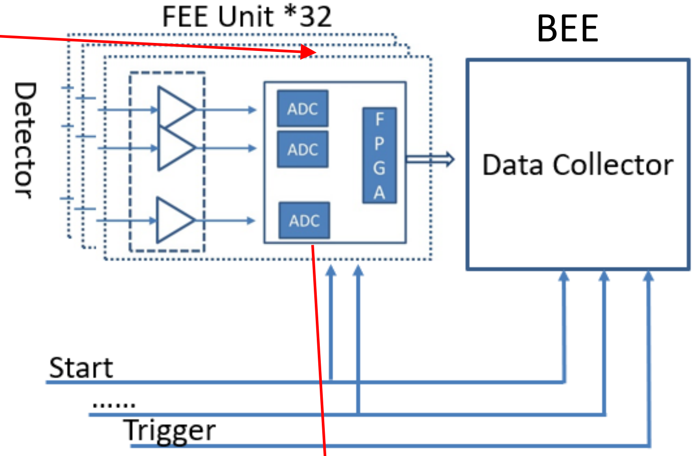
The structure is stable

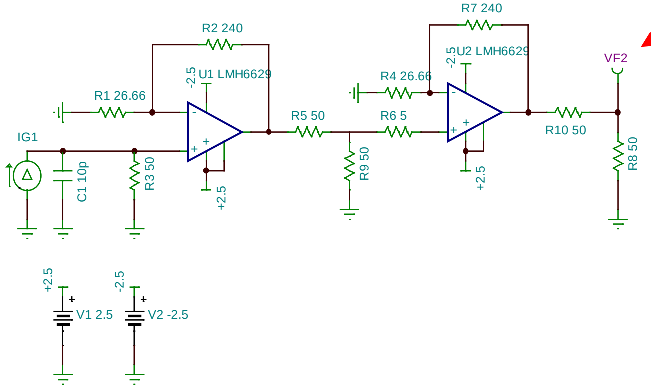
Preliminary readout scheme of Drift Chamber

Considering : radiation hardness
Power consumption,
Material budget

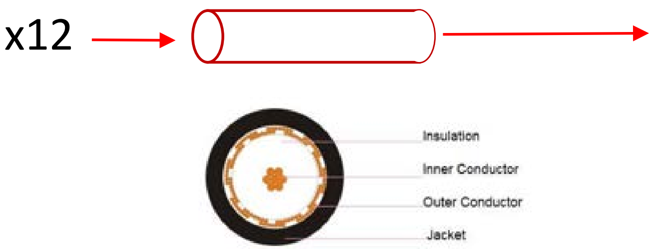
FEE-1:
Rad-hard analog preamps
FEE-2:
ADC and FPGA board for data readout and buffering, put in low dose region



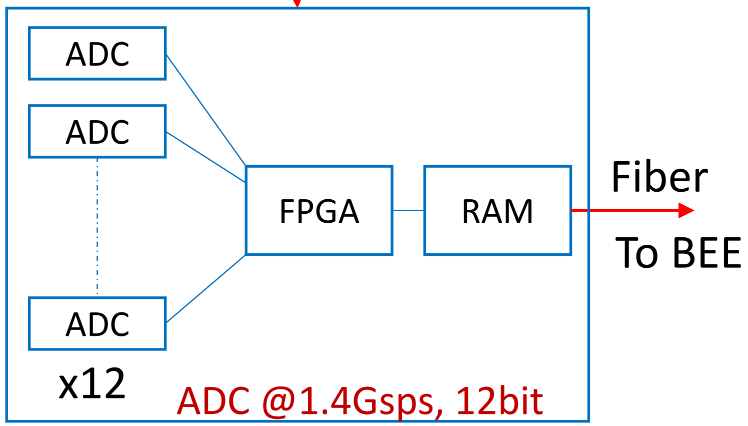




High Bandwidth Preamp
100mW/ch -> ~2.6kW in total
1.3kW for each end plate, air cooling is OK
no additional material budget



Analog signal on Cable
2.8mm per co-ax
12 signals + 1 Power
3dB attenuation @ 280MHz



0.5Gbps/12 channels--
compatible with requirement of CEPC overall readout scheme

Preliminary design parameters

R extension	600-1800mm
Length of outermost wires（cosθ=0.85）	5800mm
Thickness of inner CF cylinder: (for gas tightness, without load)	200μm
Thickness of outer CF cylinder: (for gas tightness, without load)	300μm
Outer CF frame structure	Equivalent CF thickness: 1.8 mm
Thickness of end Al plate:	20mm
Cell size:	~ 18 mm × 18 mm
Cell number	27623
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC_4H_{10}=90:10

Summary

- R&D progress of CEPC drift chamber:
  - Simulation studies show that 3.2σ K/π separation at 20GeV/c can be achieved with 1.2m track length
  - Fast electronics development is under progress. Preliminary tests validated the performance of the readout electronics and the feasibility of dN/dx method
  - Cluster counting reconstruction algorithm with deep learning shows promising performance for MC samples and test data
  - Preliminary mechanical design and FEA show the structure is stable
  - Global electronics scheme is reasonable

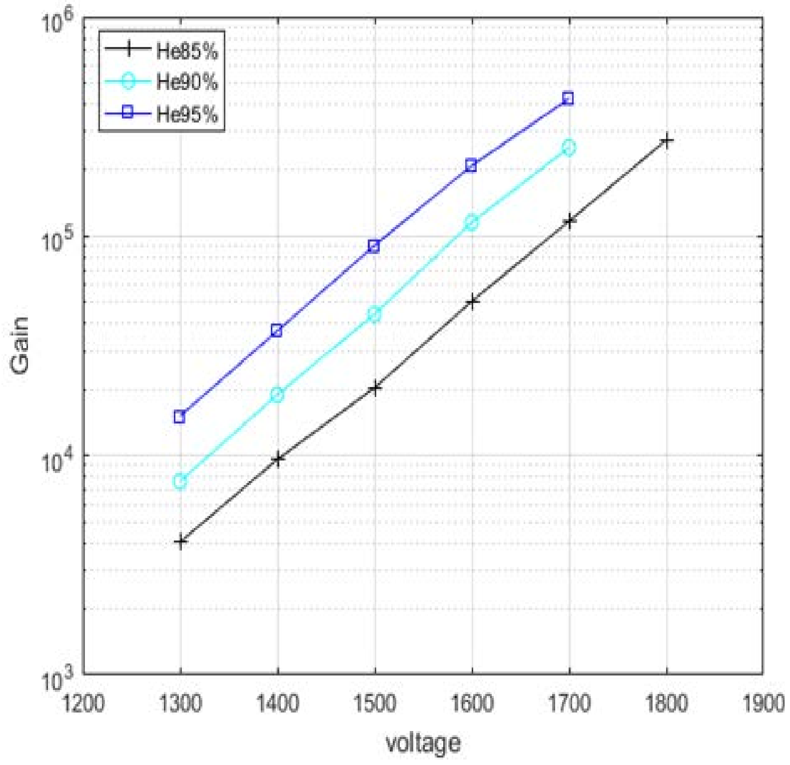
- Further study plan
  - Fine detector optimization
  - Optimize deep learning algorithm and FPGA implementation
  - Prototyping and testing with full-length cells (mechanics, manufacturing, testing)

Thanks for your attention

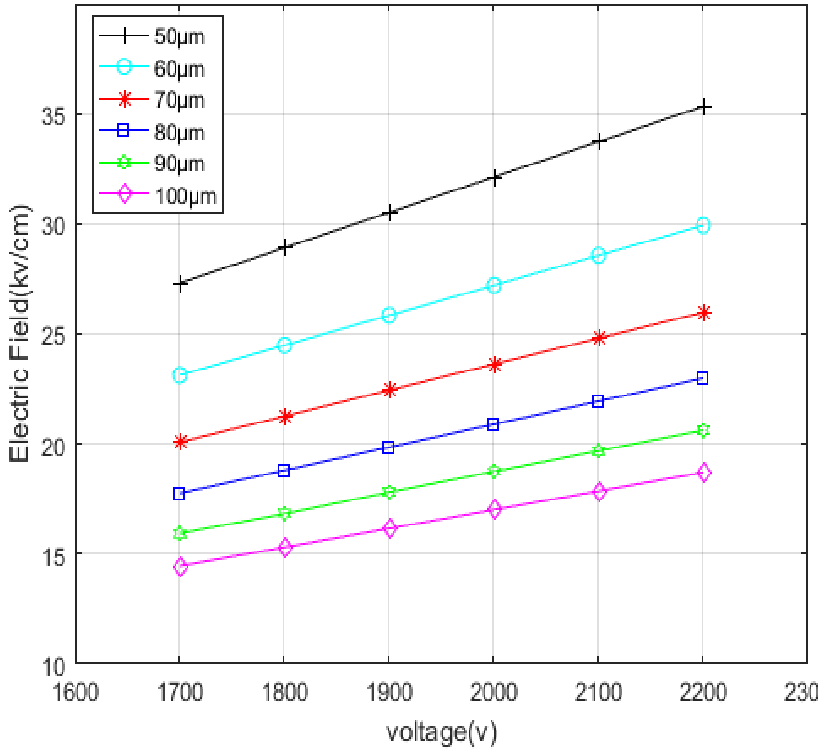
Backup

Garfield++ simulation

Gain vs HV



Electric field on the surface of field wires vs HV



Electric field on the surface of sense wires vs diameter of field wires