R&D Progress of Drift Chamber for CEPC

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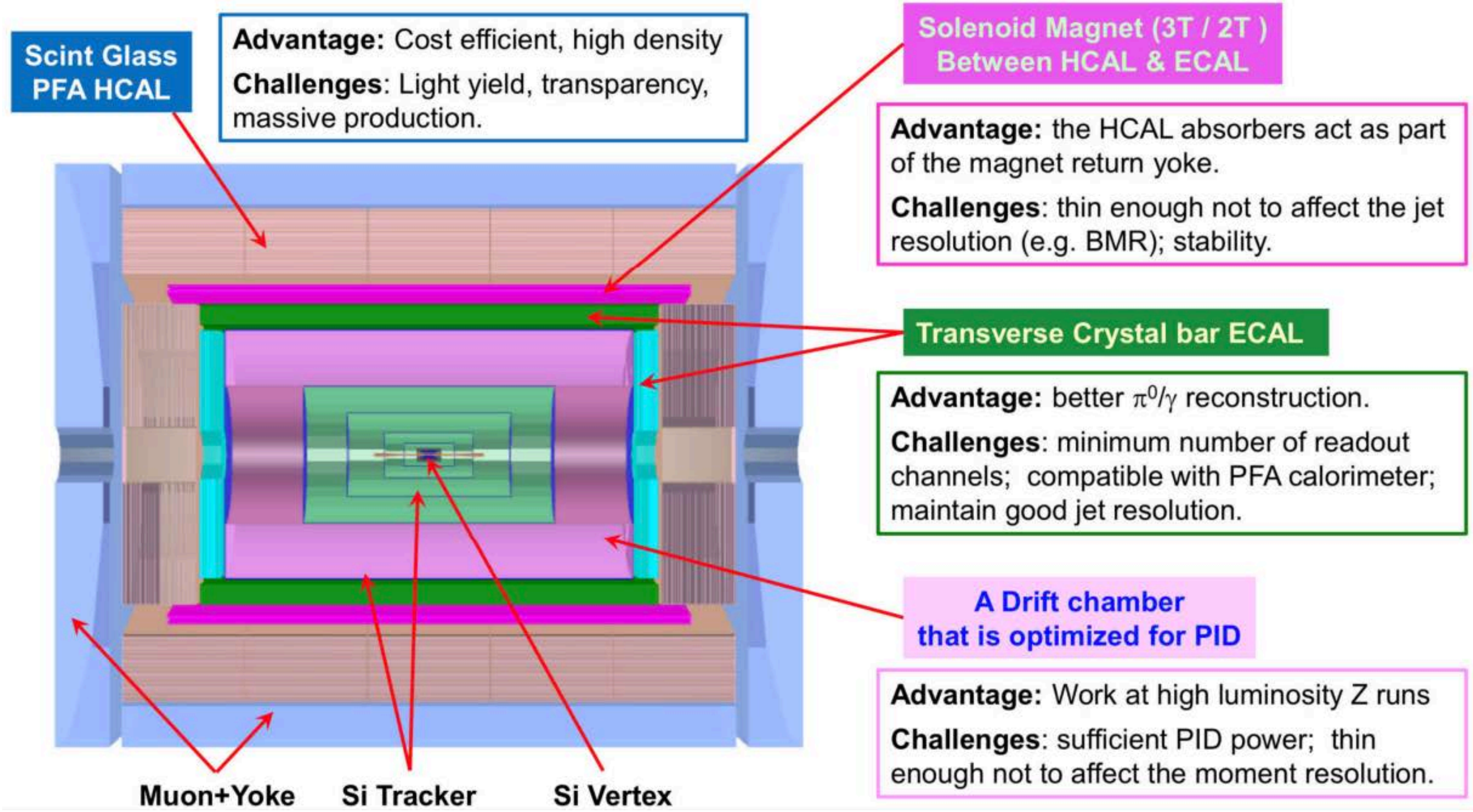
On behalf of DC group

2024.4.10

Outline

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

Drift Chamber in CEPC 4th conceptual detector

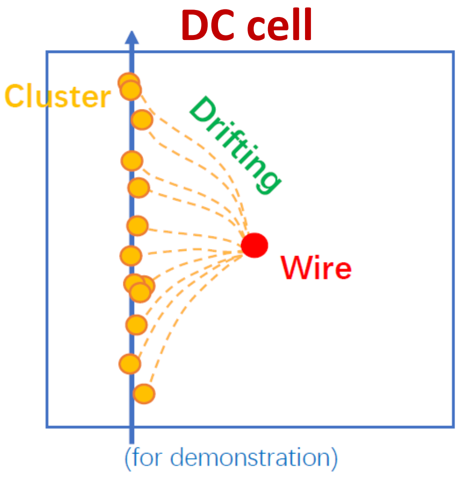


PID is essential for CEPC, especially for flavor physics

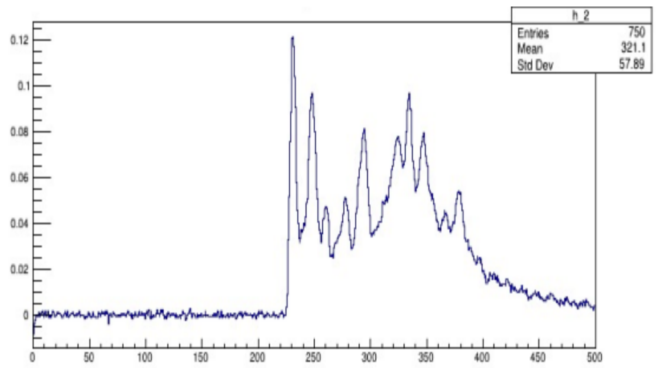
- The drift chamber optimized for PID with cluster counting technique
- Require better than 3σ separation power for K/π with momentum up to 20GeV/c
- Benefits tracking and momentum measurement

Ionization measurement with dN/dX

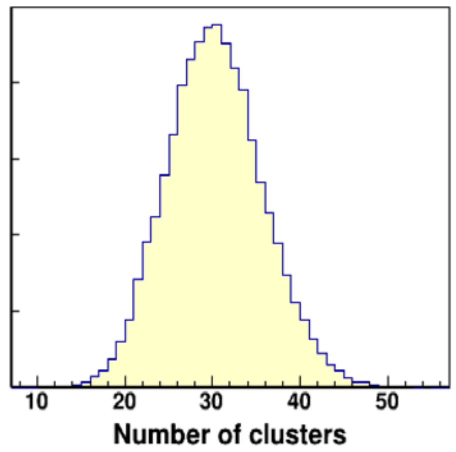
- Measure number of clusters over the track, the number of clusters corresponds to the number of the primary ionization
- Yield of primary ionization is Poisson distribution
- To eliminate the effects of secondary ionization, dN/dx is based on peak finding and clusterization



Induced current



Peak finding +clusterization



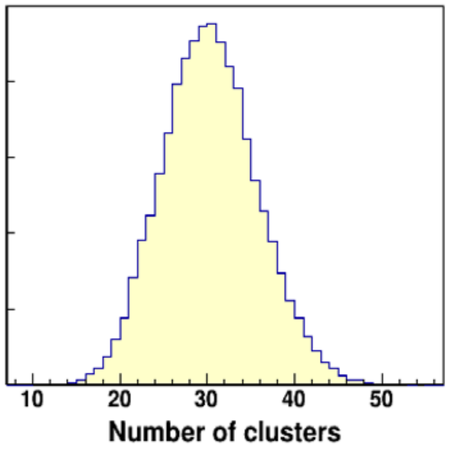
Primary ionization

dN/dx vs dE/dx

dN/dx

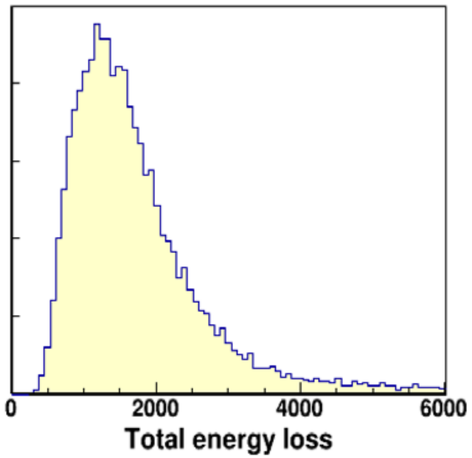
- Number of primary ionization clusters per unit length
- Poisson distribution
- Small fluctuation

Cluster counting technique

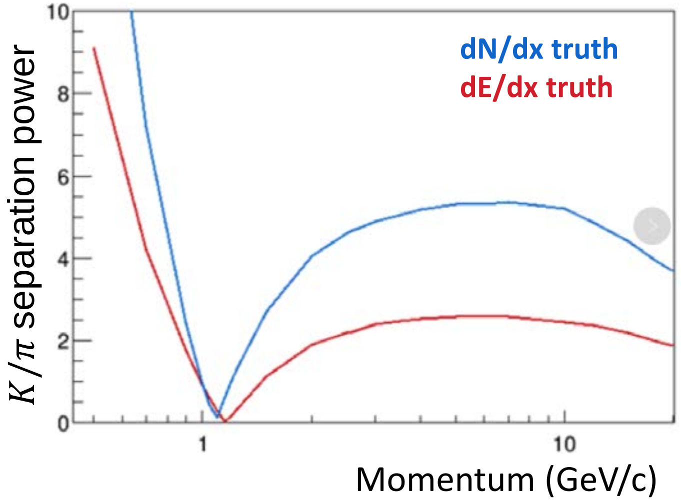


dE/dx

- Energy loss per unit length
- Landau distribution
- Large fluctuation



K/π separation power
dN/dx vs dE/dx



dN/dx has a much better (2 times) K/π separation power up to 20 GeV/c compared to dE/dx (Simulation)

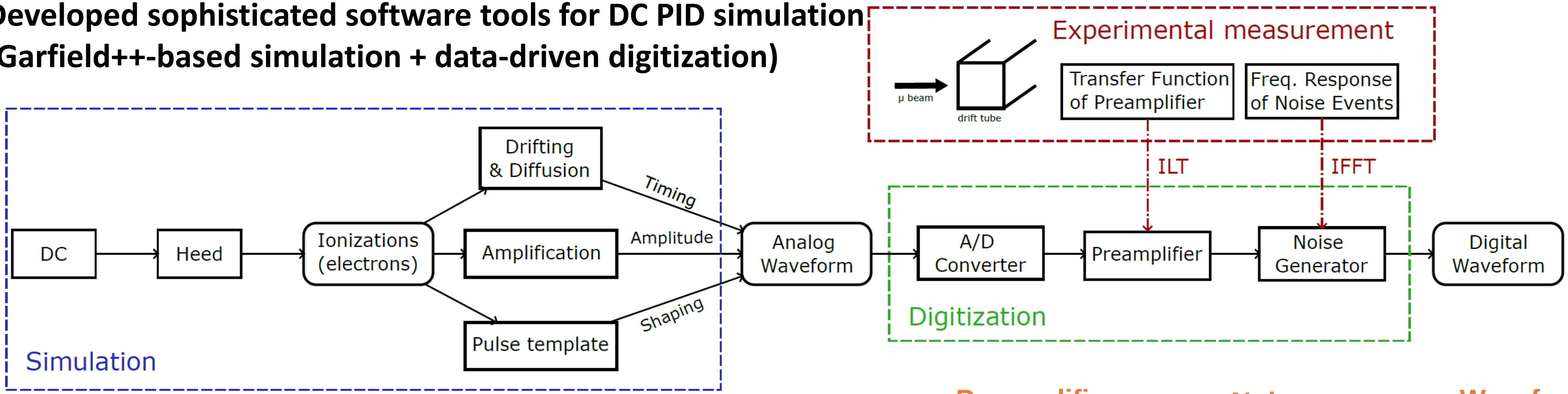
Key issues with dN/dx measurement

- Detector optimization and performance study
  - 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
  - dN/dx resolution and PID capability
- Waveform test
  - Fast and low noise electronics
- dN/dx reconstruction algorithm
  - Identifying primary and secondary ionization signals
  - Reducing noise impacts

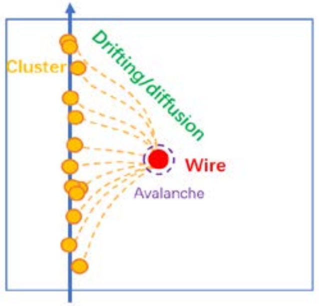
Performance study and Detector R&D

Waveform-based full simulation

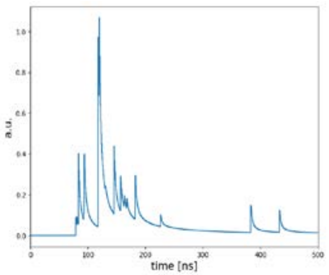
Developed sophisticated software tools for DC PID simulation (Garfield++-based simulation + data-driven digitization)



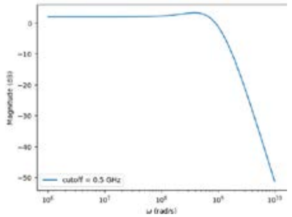
DC cell



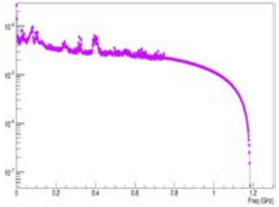
Induced signal



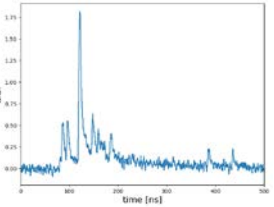
Preamplifier



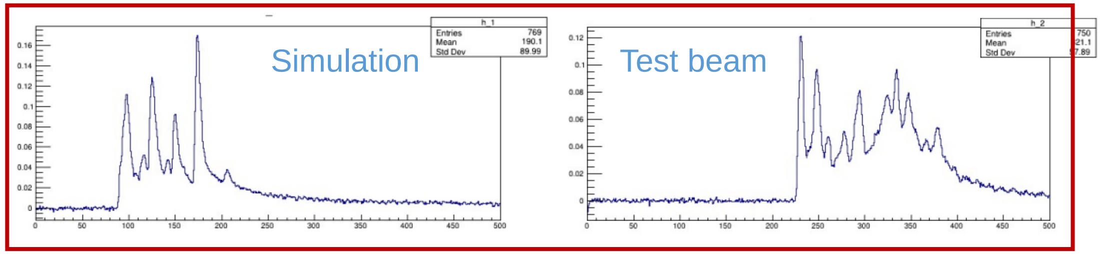
Noise



Waveform



Tuned MC is comparable to data

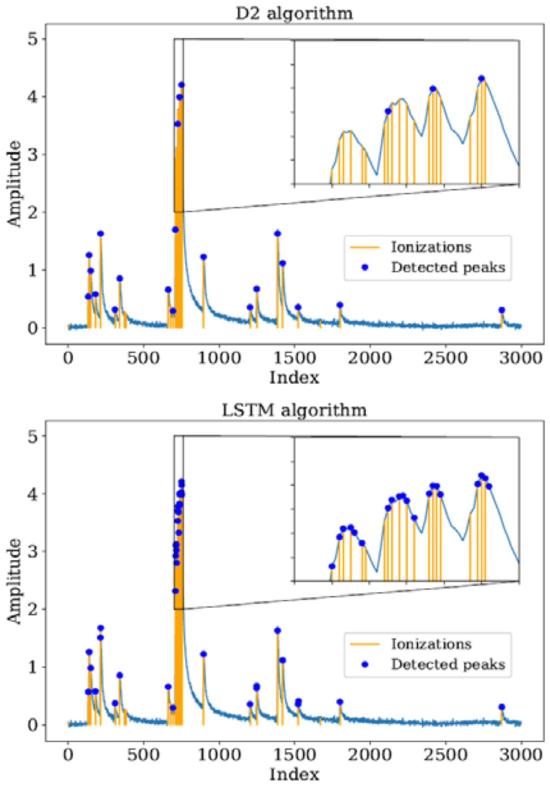


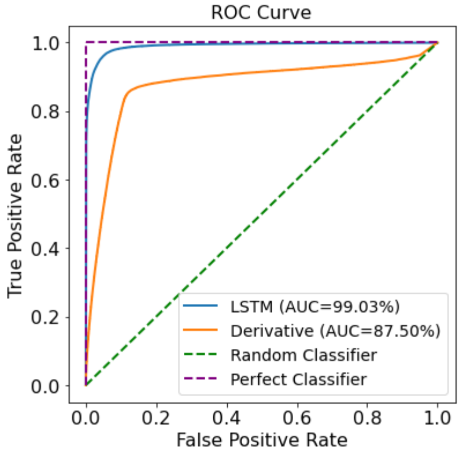
Machine learning reconstruction algorithm

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

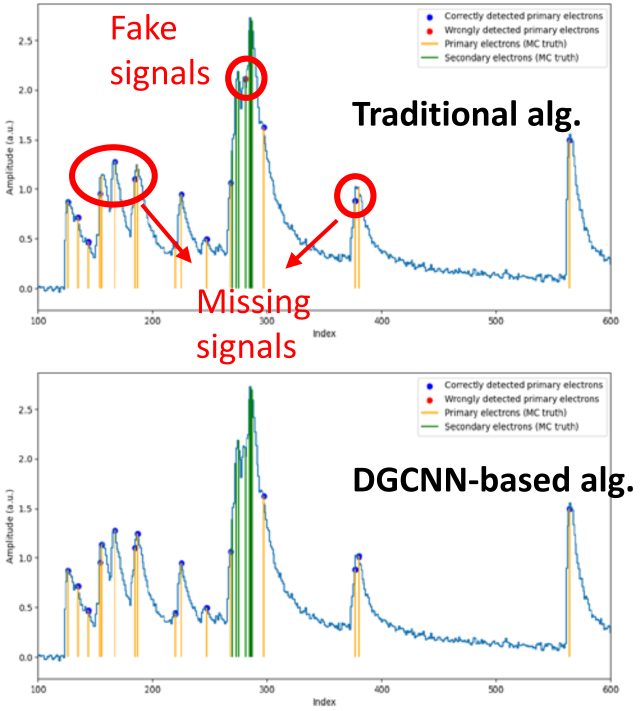
See Guang's talk for more details

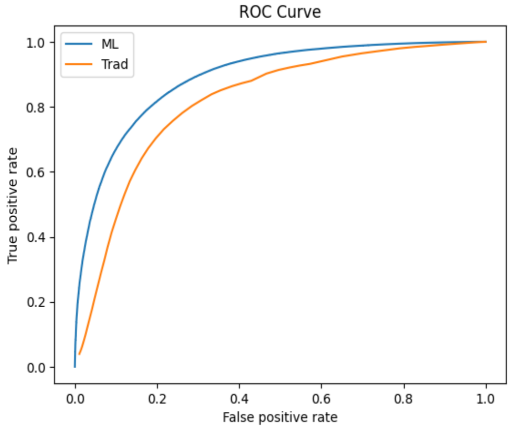
Long Short-Term Memory (LSTM)-based peak finding
higher efficiency than the derivative-based algorithm, especially for the pile-up recovery



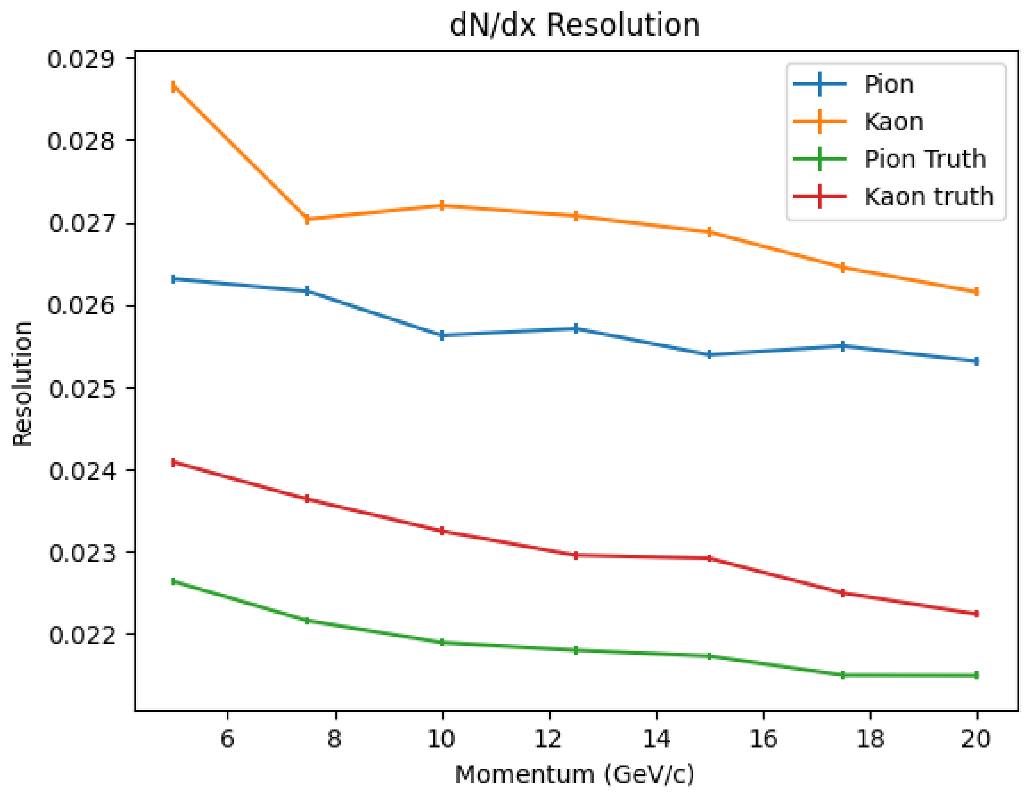


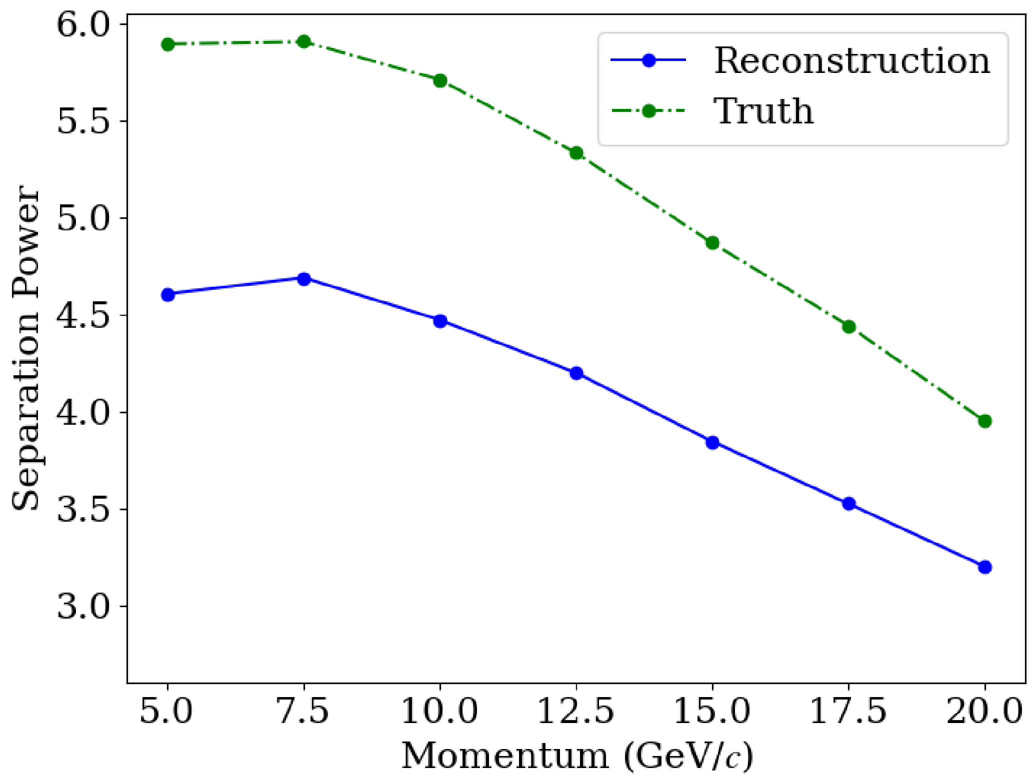
Dynamic Graph CNN (DGCNN)-based clusterization
higher efficiency, and lower fake rate





dN/dx Resolution

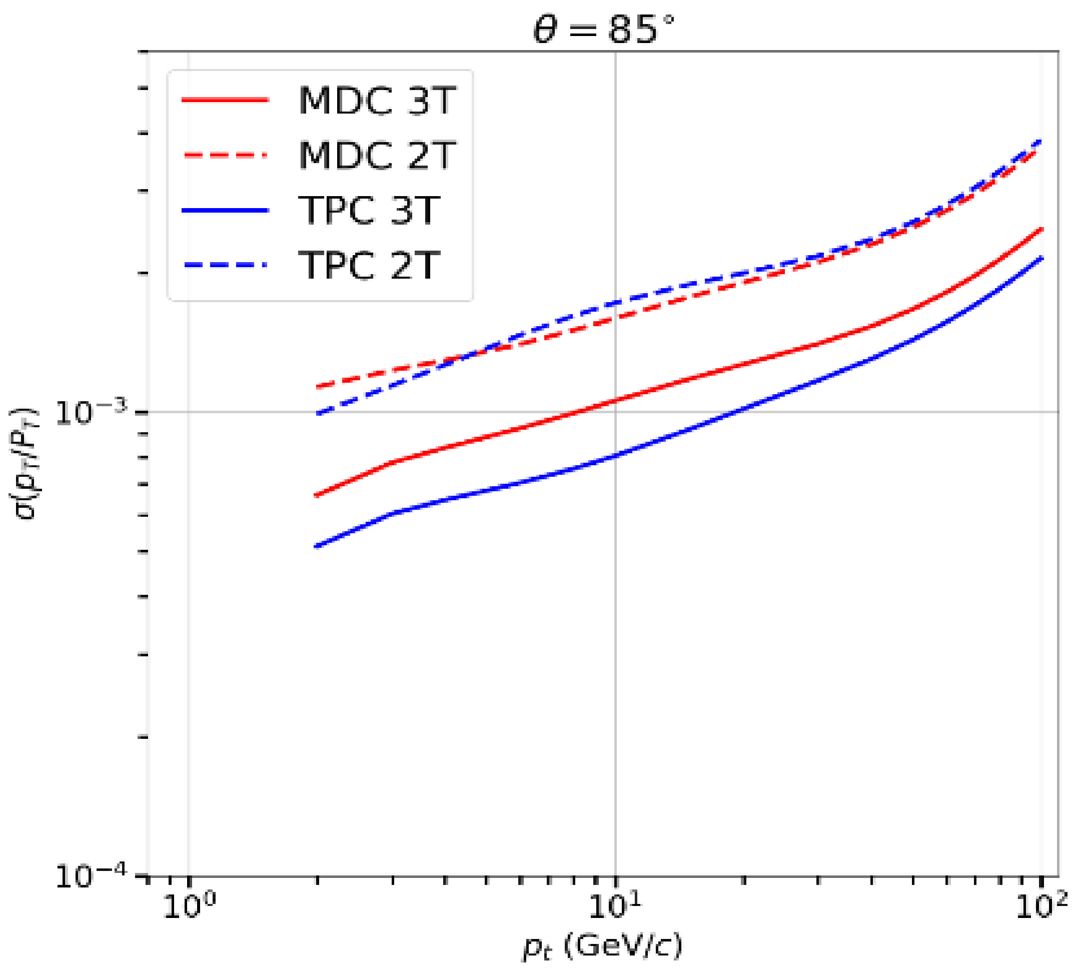




- dN/dx resolution: 2.5%-2.6% for pion
- 2.6%-2.7% for Kaon

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

Momentum Resolution

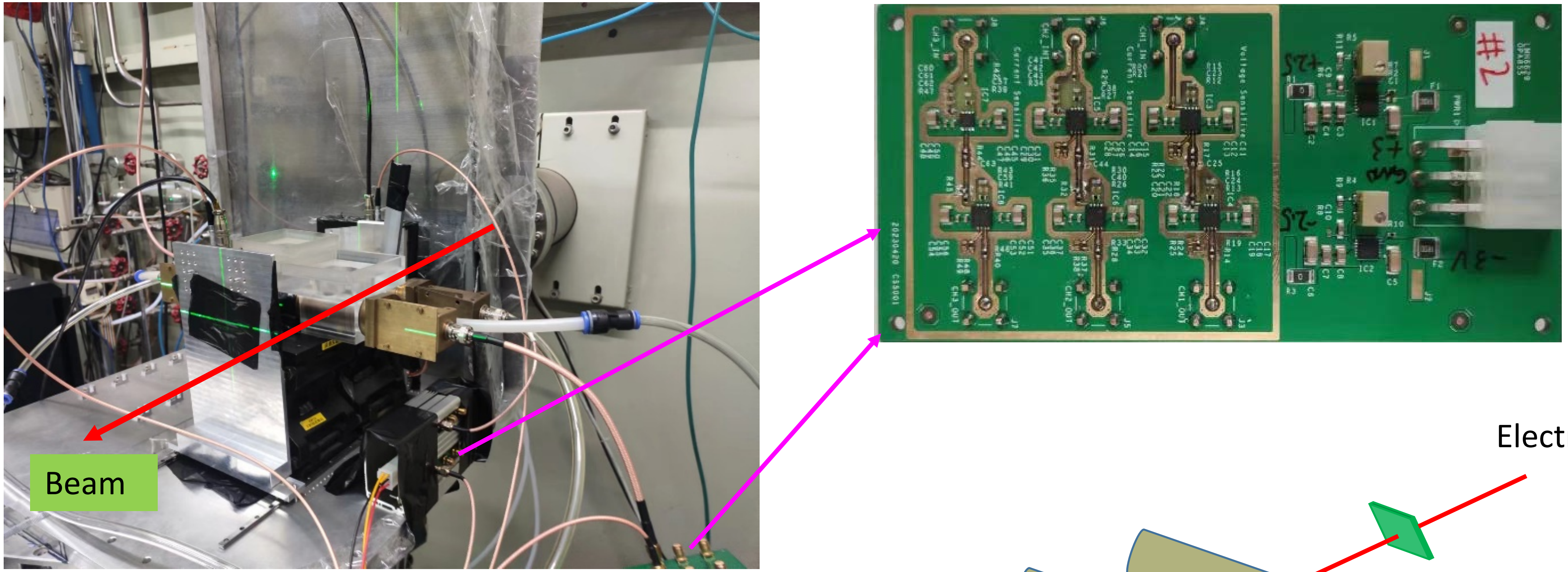


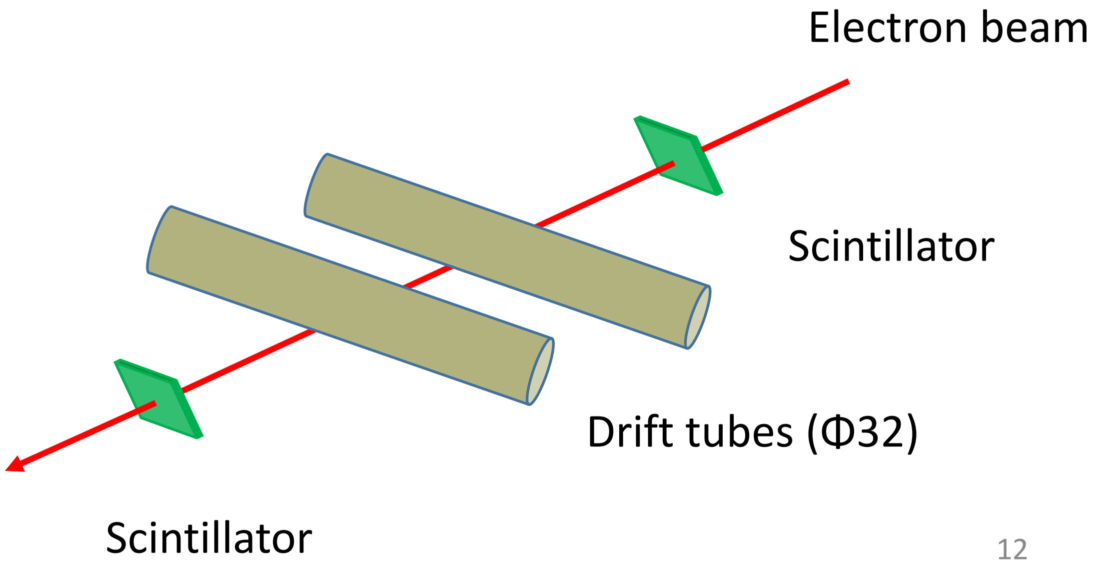
$\sigma(1/pT) = a \pm b/pT$

	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

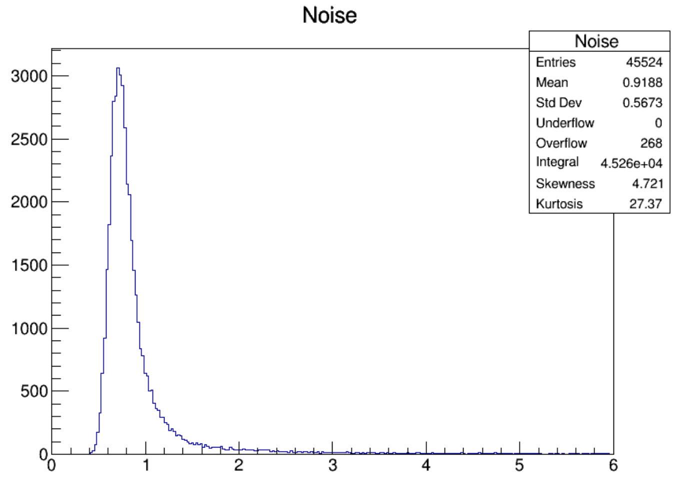


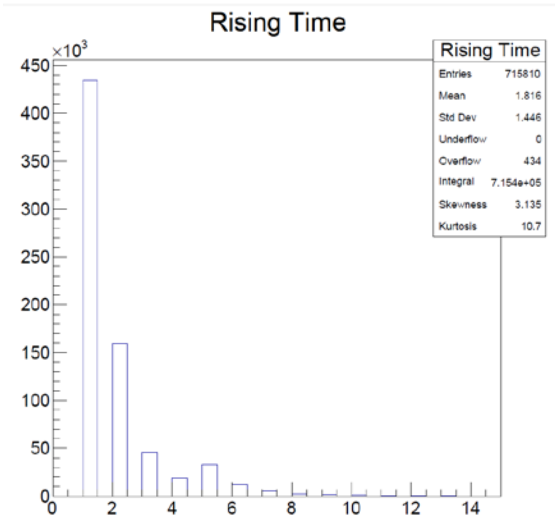


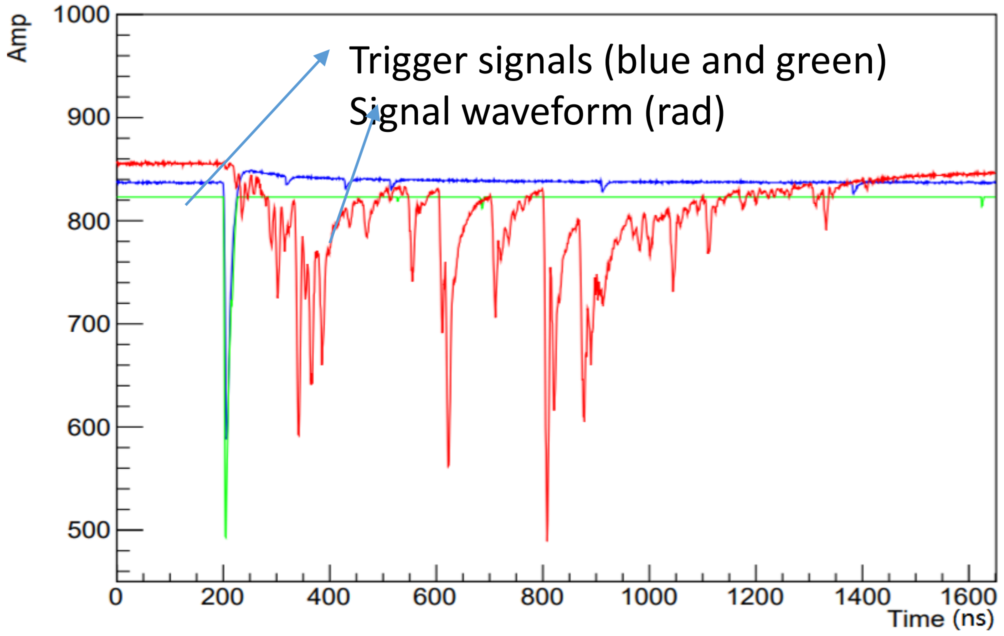
- Developed fast and high bandwidth preamps
- Tested with electron beam at IHEP
    - Two drift tubes + preamps + ADC (1GHz)
    - Two scintillators provide trigger signals

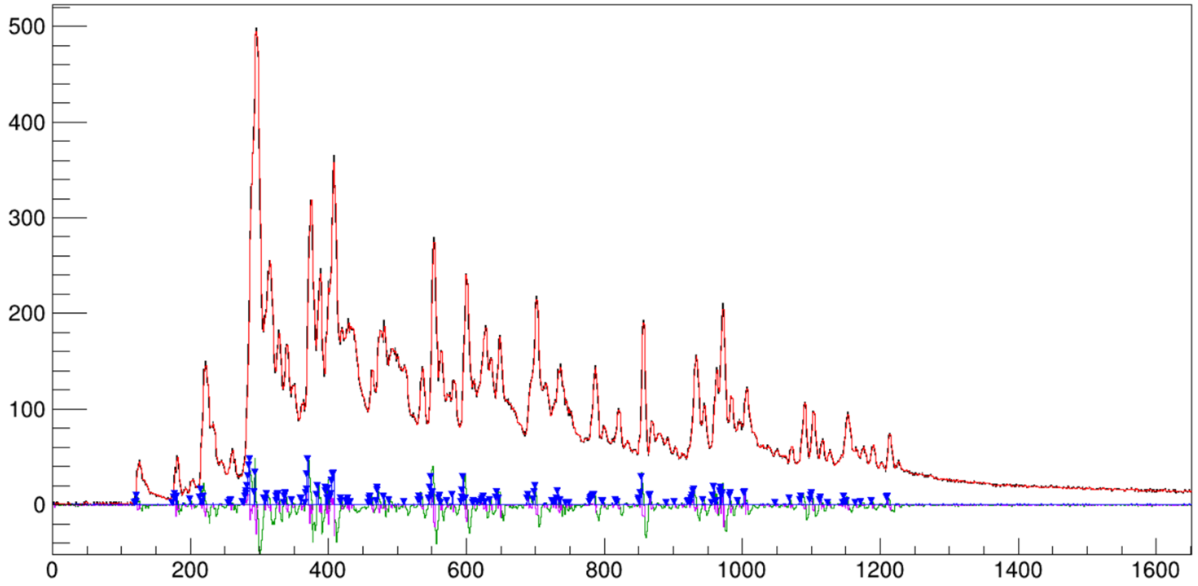
Preliminary results

- Low noise and high bandwidth preamplifiers
- Rise time : ~ ns
- Clear peaks

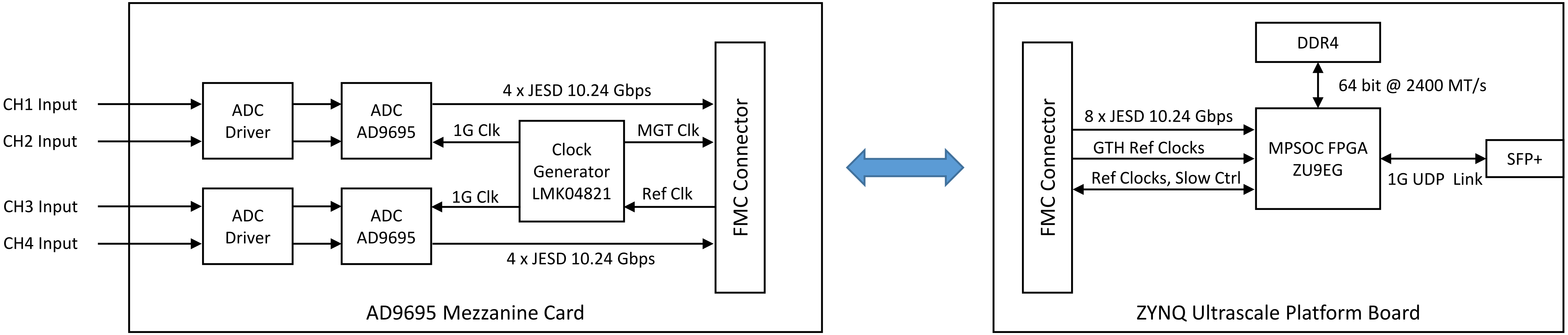


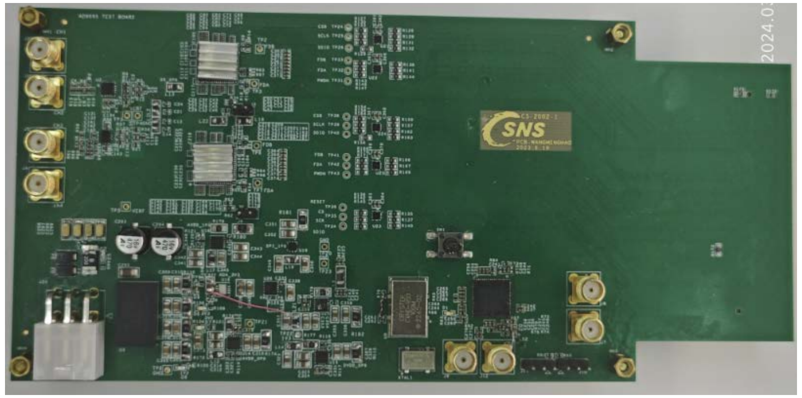


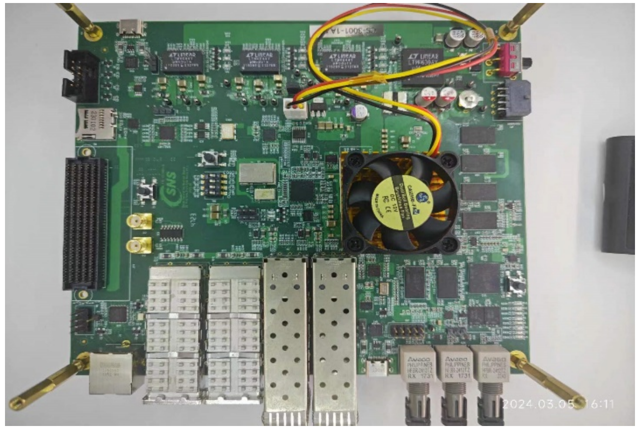




Readout electronics design



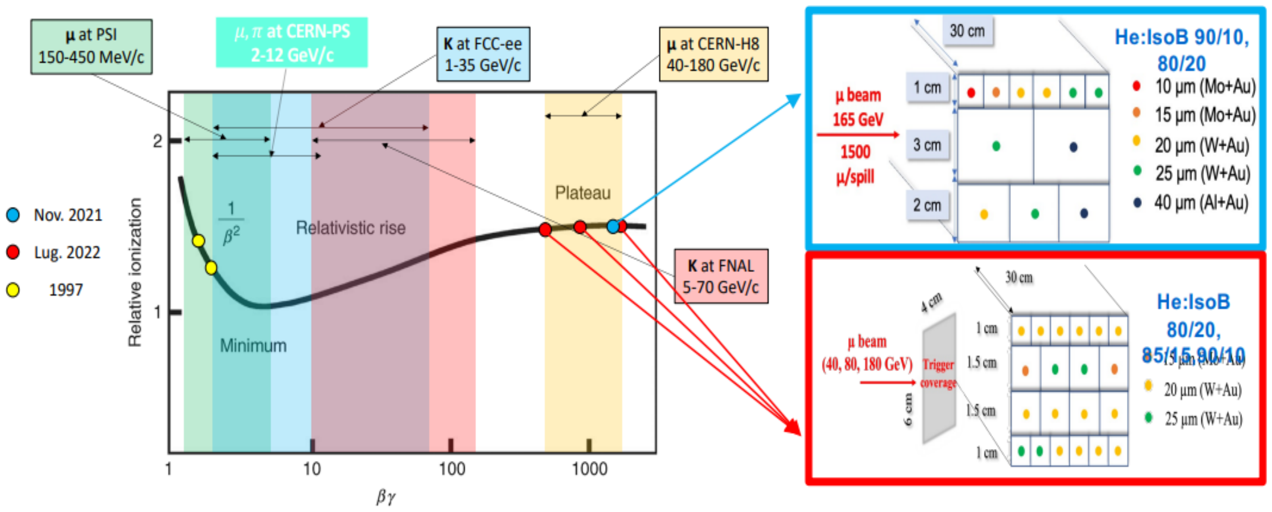


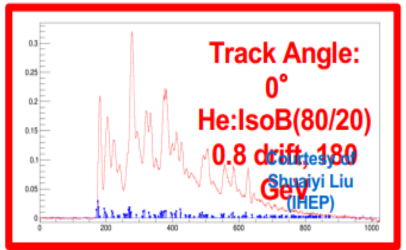


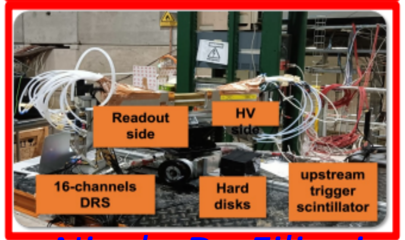
- The readout prototype system is developed to verify basic functions, consisting of an ADC board and an FPGA board. will be integrated into one board in next version
- The ADC sub card is based on two high-speed ADCs (ADI AD9695), 14 bit resolution, and a maximum sampling of 1.4 Gsps

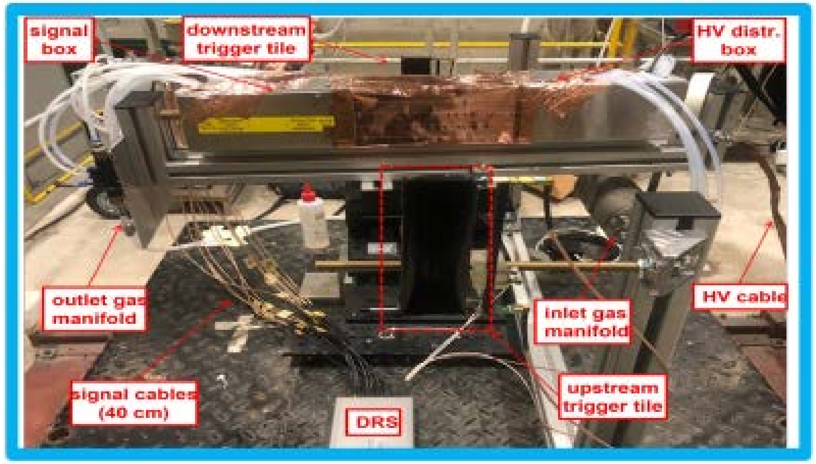
Synergy with IDEA, Collaboration with INFN

- Beam tests organized by INFN group:
  - Two muon beam tests performed at CERN-H8 (βγ > 400) in Nov. 2021 and July 2022
  - A muon beam test (from 4 to 12 GeV/c) in 2023 performed at CERN
  - Ultimate test at FNAL-MT6 in 2024 with π and K (Bγ = 10-140) to fully exploit the relativistic rise.
- Contributions from IHEP group:
  - Participate data taking and collaboratively analyze the test beam data
  - Develop the machine learning reconstruction algorithm



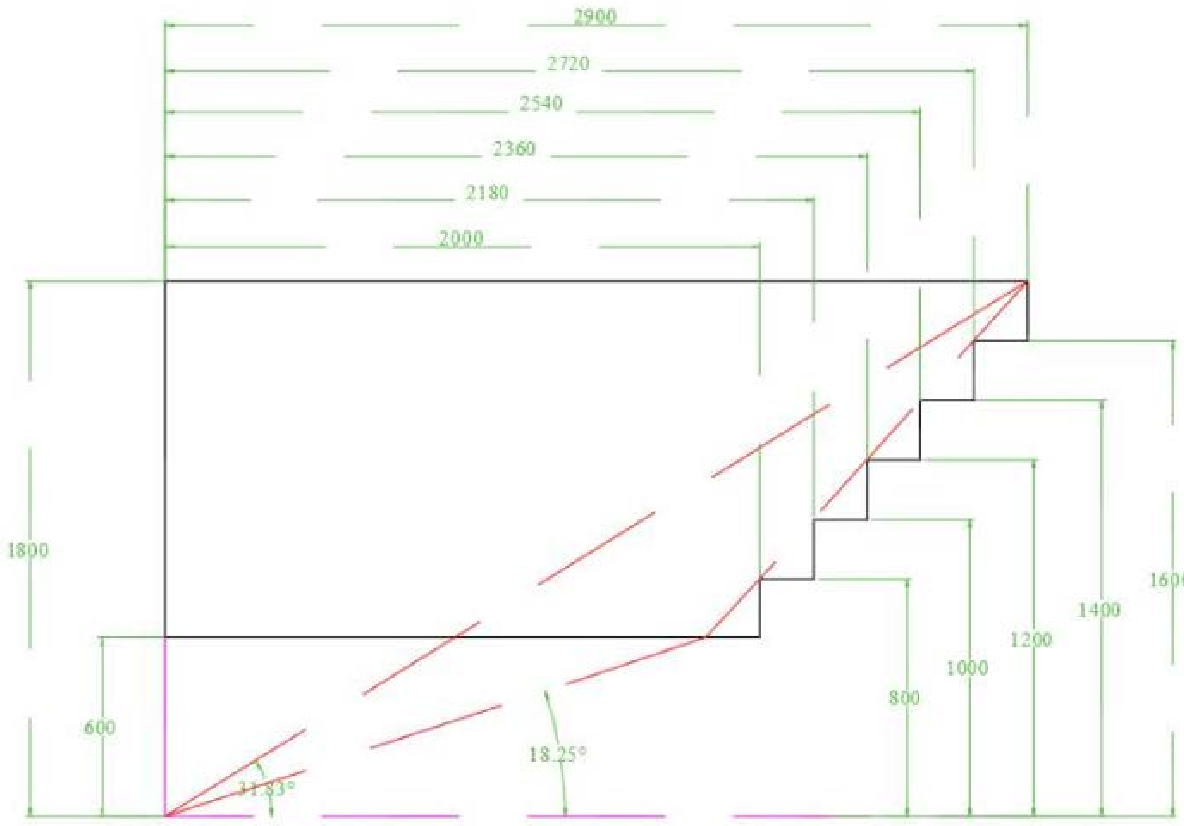


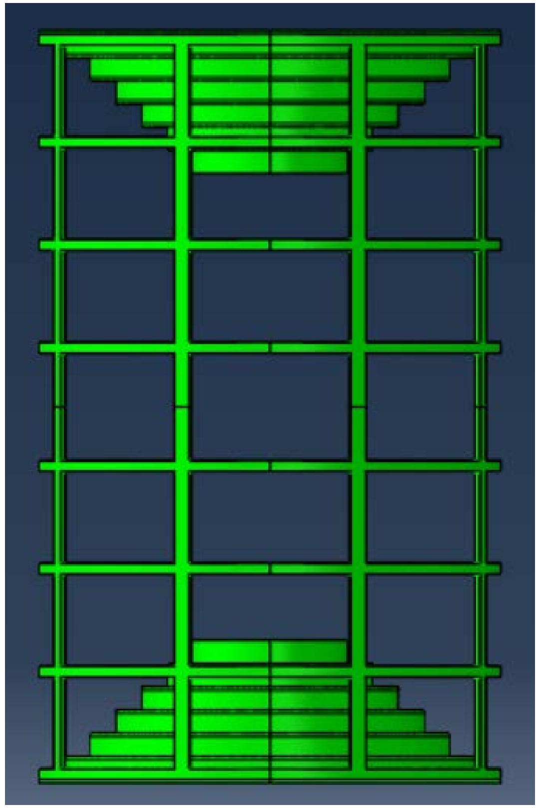


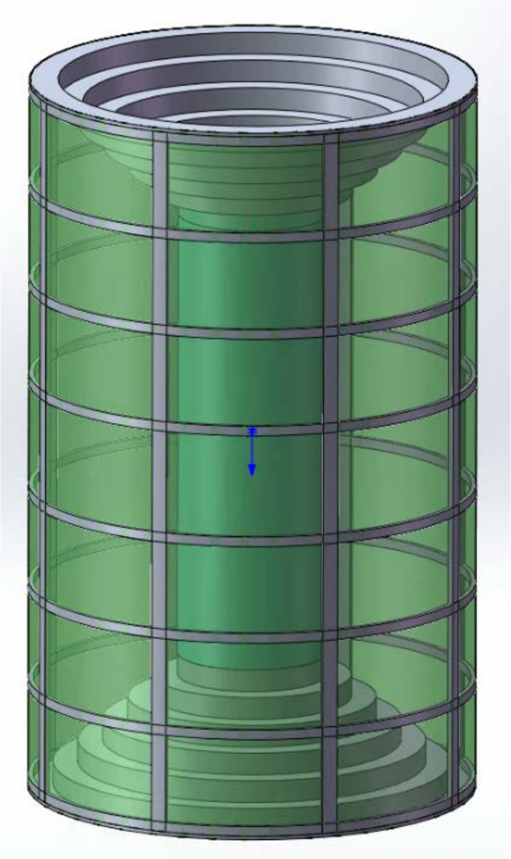


Preliminary Mechanical Design

Overall Design (preliminary)



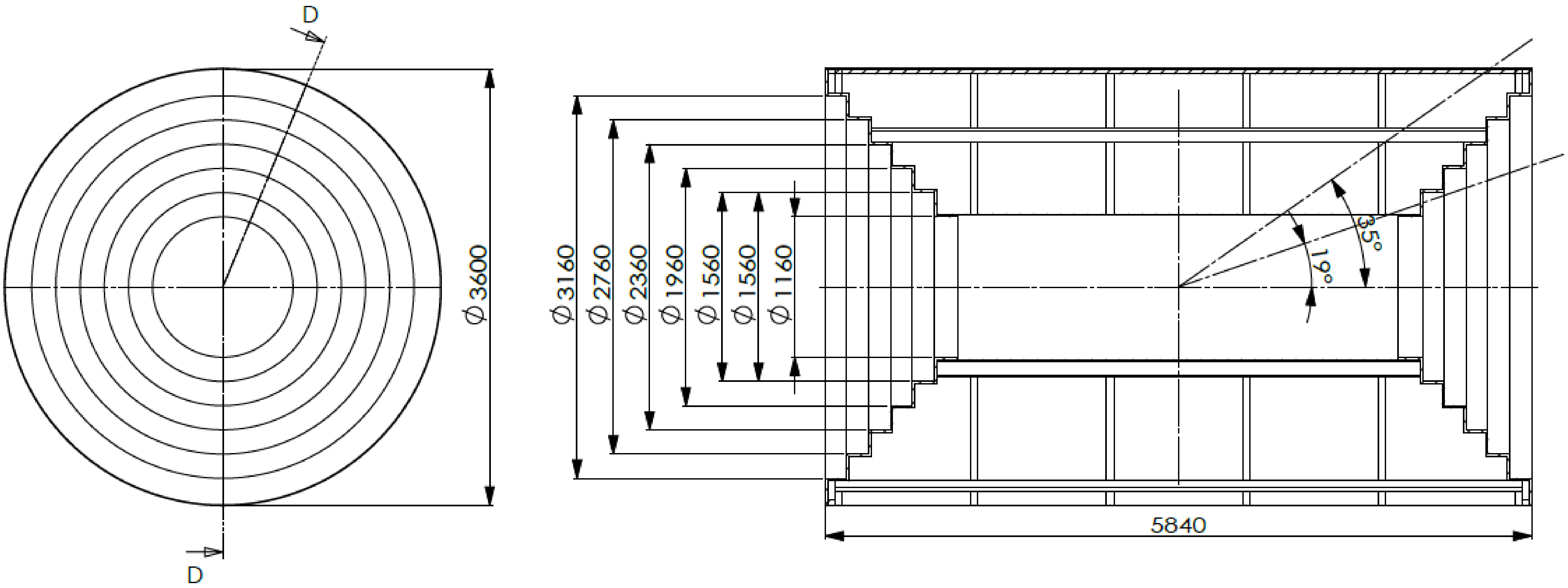




CF Frame structure： 8 longitudinal hollow beams + 8 annular hollow beams + inner CF cylinder and outer CF cylinder

- Length : 5800mm
- Outer diameter: 3600mm， Inner Diameter: 1200mm；
- Thickness of each end plate: 25mm/20mm， weight :1100kg /880kg

Overall Design



- Stepped end plates design
- Can Provide space for end cap Si tracker and it is easy to fix the barrel Si tracker

Wire tension

	cell number /step	length	single sense wire tension(g)	Single field wire tension(g)	total tension /step (kg)
	2684	4000	43.29	66.52	651.78
	3452	4360	51.43	79.03	995.95
	4220	4720	60.28	92.62	1426.88
	4988	5080	69.82	107.29	1953.63
	5756	5440	80.07	123.03	2585.27
	6524	5800	91.02	139.85	3330.85
total	27623				10944

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

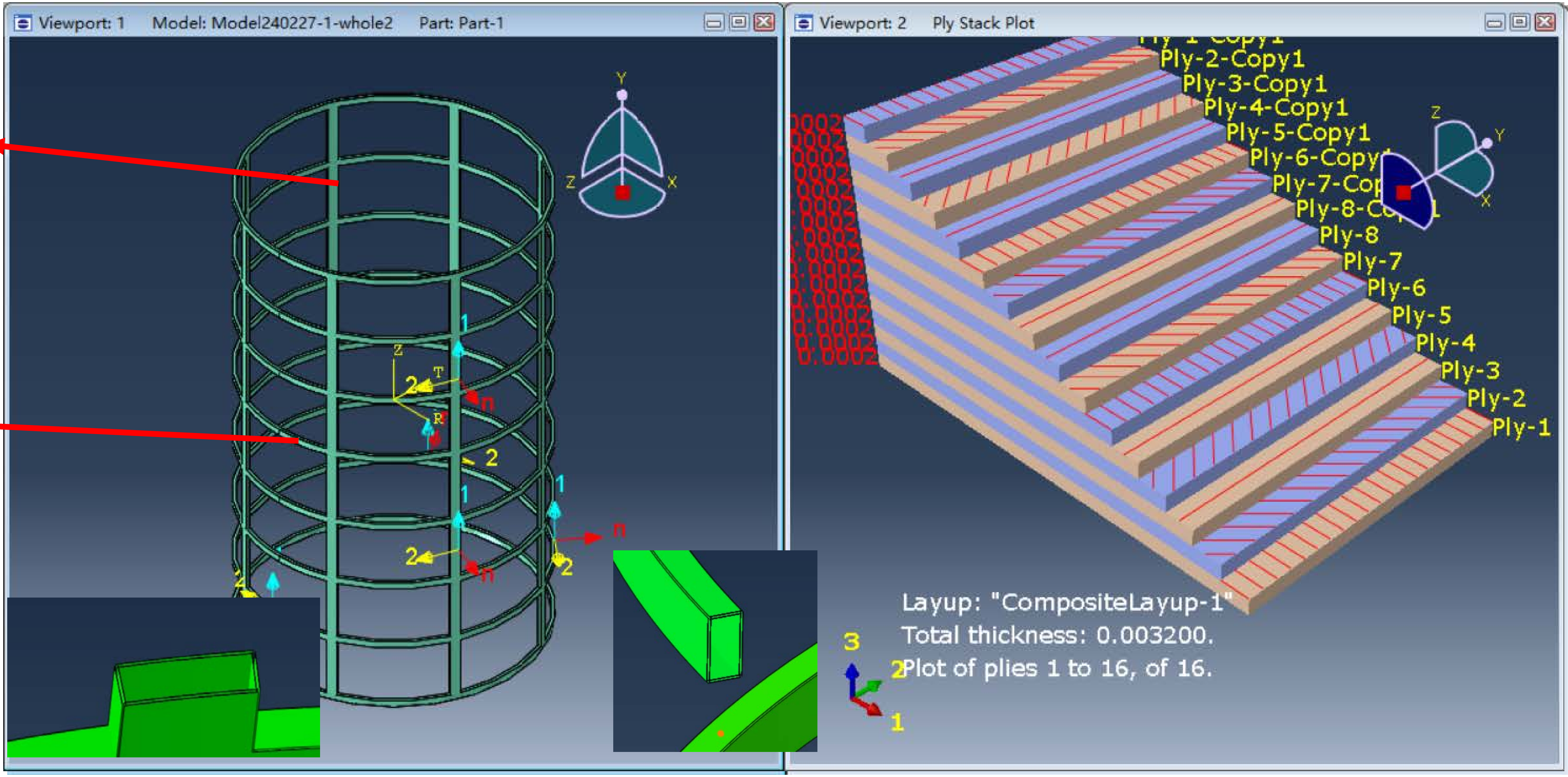
Meet requirements of stability condition:

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

Finite Element Analysis

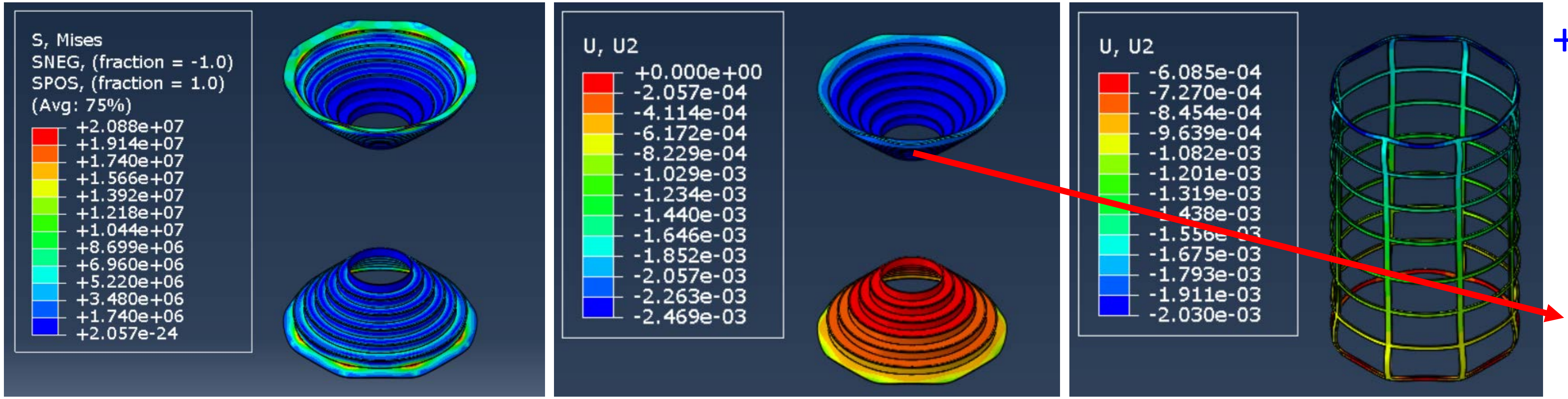
Cross section of longitudinal HB：125mm*40mm，thickness: 3.2mm weight：78kg

Cross section of annular HB：80*40mm Thickness: 3.2mm weight：111kg



Thickness of CF wall: 3.2mm， including 16 composite layers. Thickness of each composite layer: 200μm

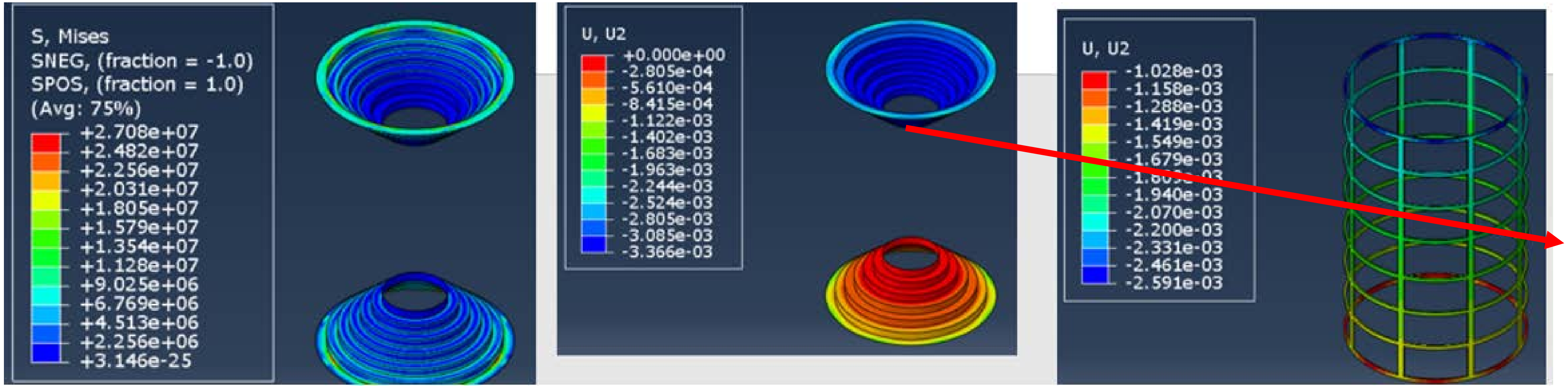
Results of FEA



Loads: Wire tension + Axial self weight

End plate thickness: 25mm

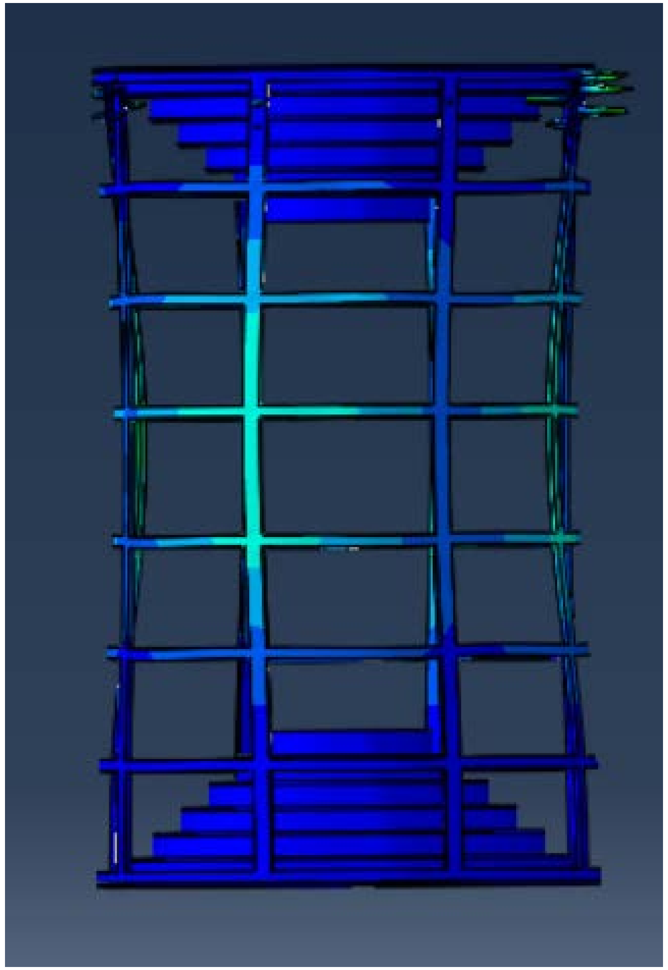
- Stress 20.9MPa,
- Endplate deformation 2.5mm,
- CF frame deformation 1.4mm



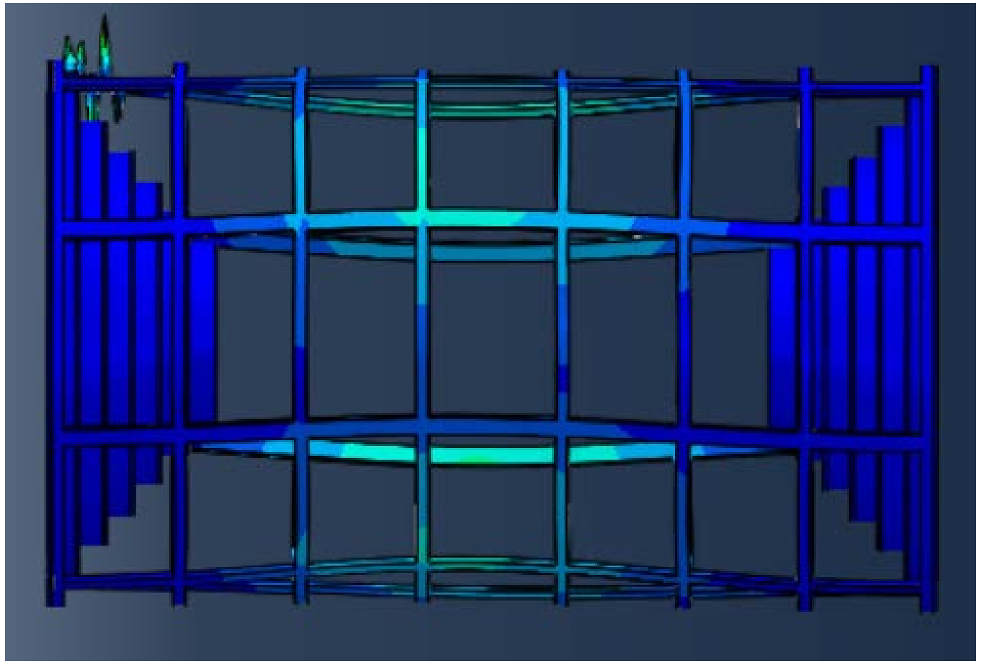
End plate thickness: 20mm

- Stress 27.1MPa,
- Endplate deformation 3.4mm,
- CF frame deformation 1.6mm

Results of FEA



Vertical self weight
Buckling coefficient : ~12



Horizontal self weight
Buckling coefficient : ~14

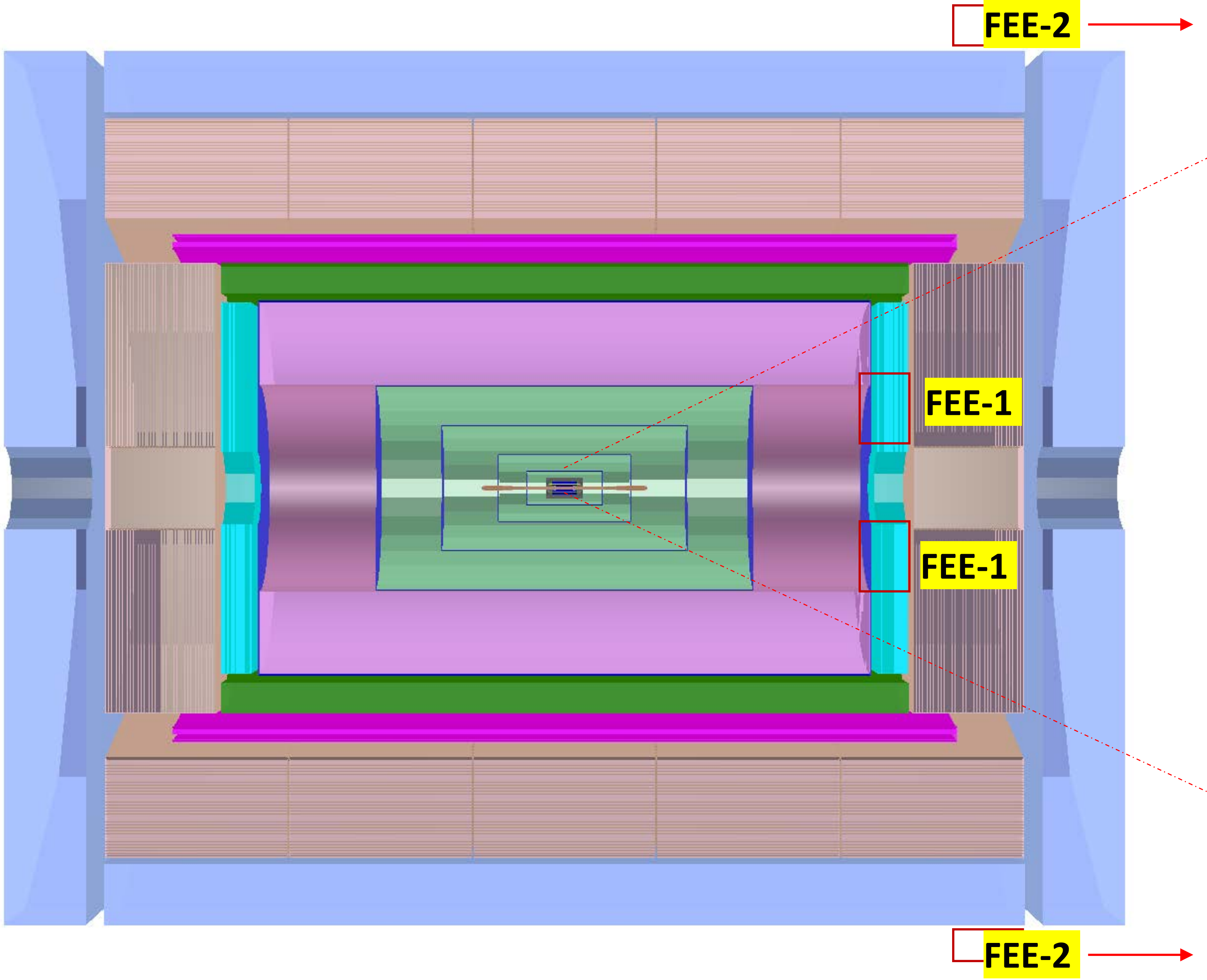
The structure is stable

Updated 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 / 25mm
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

Overall Scheme for Electronics

Global design for DC Elec-TDAQ system



To BEE

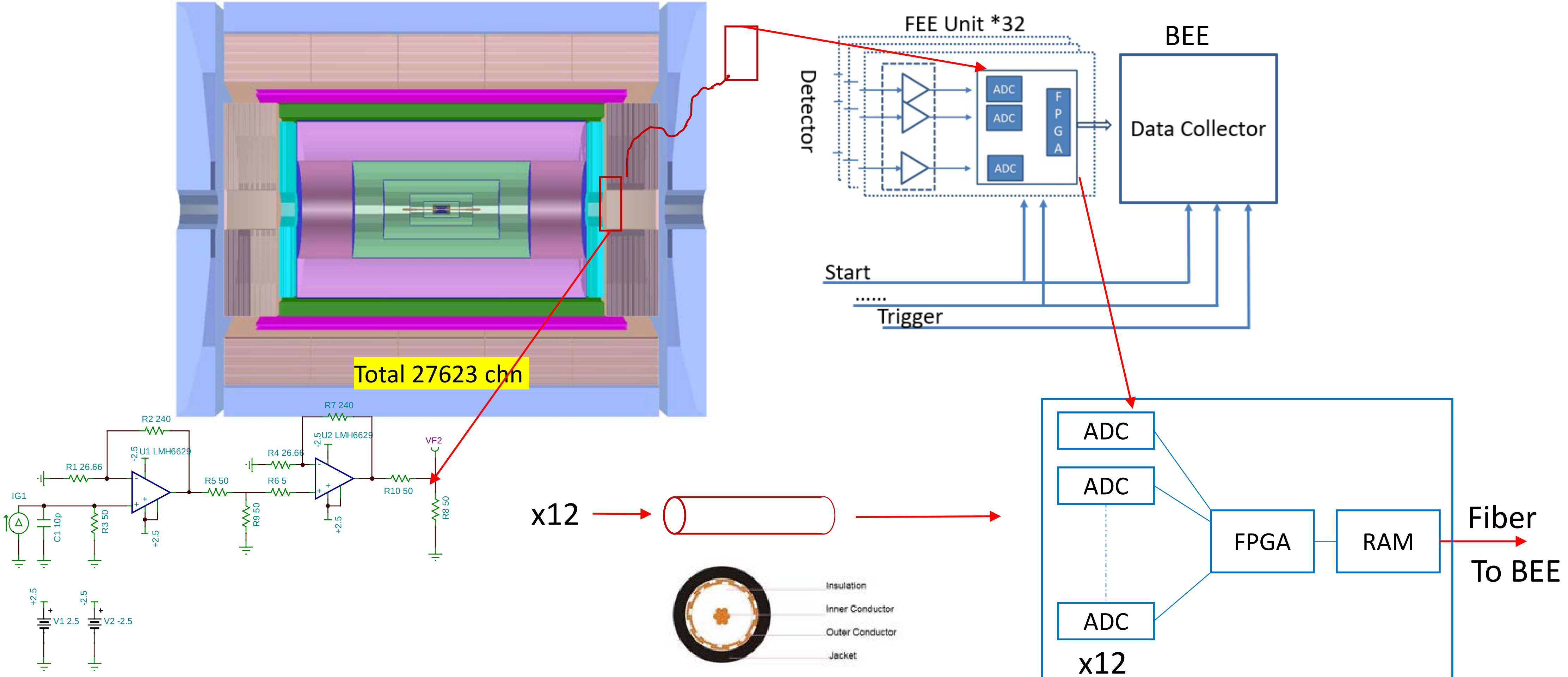
Considering : radiation hardness
Power consumption,
Material budget

FEE-1:
A rad-hard (analog) FEE (preamp)

FEE-2:
Non rad-hard FEE for data buffering, in low dose region (ADC and FPGA)

To BEE

Preliminary readout scheme of Drift Chamber



High Bandwidth Preamp
100mW/ch -> 2.7kW in total

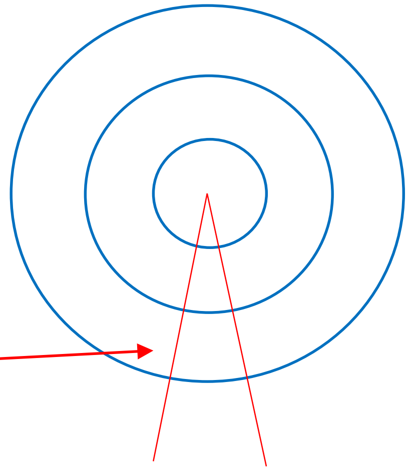
1.4kW for each end plate, air cooling is OK
no additional material bufget

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

ADC @1.3Gsps, 12bit

Data size estimation

- ADC sampling rate : 1.3Gsps, 12bit, sampling window: 1.5 μs, data size/single hit: 2k×2Byte
- Hit rate of the inner most layer: ~ 70kHz/cell， outer most layer: 10kHz /cell，average hit rate: ~30kHz/ cell
- Average Occupancy: 5% (10.5% for inner most layer, 1.2% for outer most layer)
- Each digital board corresponds to 12 preamplifier channels (sector includes inner to outer layers)
- Data size estimation：
  - 0.5Gbps/12 channels-- compatible with calibration requirement and overall readout scheme of the detector



12 chn in each sector

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
  - Development of fast electronics is under progress. Preliminary tests validated the performance of the readout electronics and the feasibility of dN/dx method
  - Cluster counting reconstruction algorithm based on deep learning is developed and shows promising performance for MC samples and test data
  - Preliminary mechanical design and FEA show the structure is stable under loads of wire tension and self weight
  - Global electronics scheme is reasonable

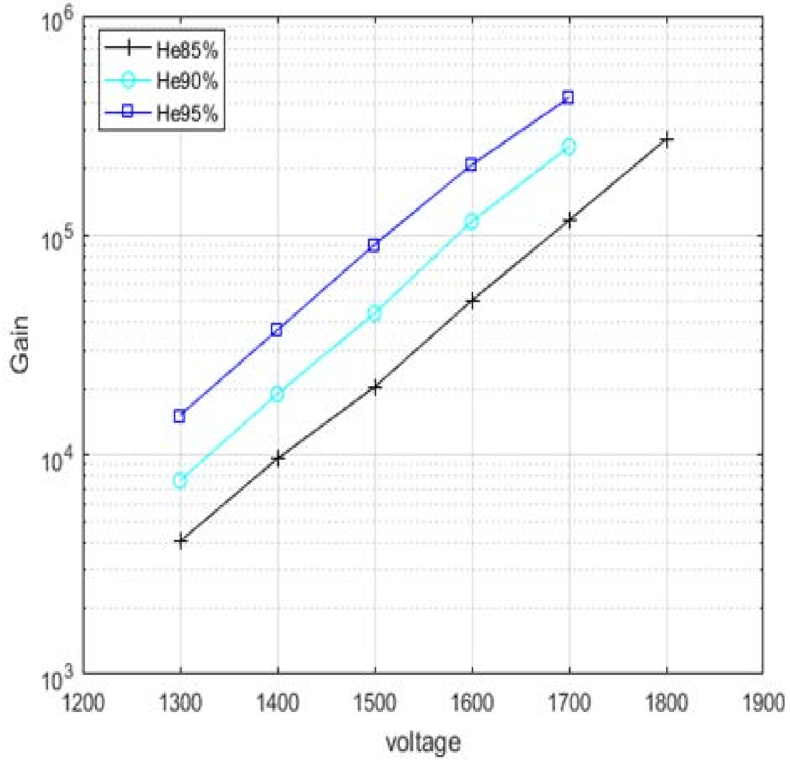
- Further study plan
  - Optimization of mechanical design
  - Detector optimization and performance study
  - dN/dx reconstruction algorithm
  - Prototyping and testing with full-length cells (mechanics, manufacturing, testing)

Thanks for your attention

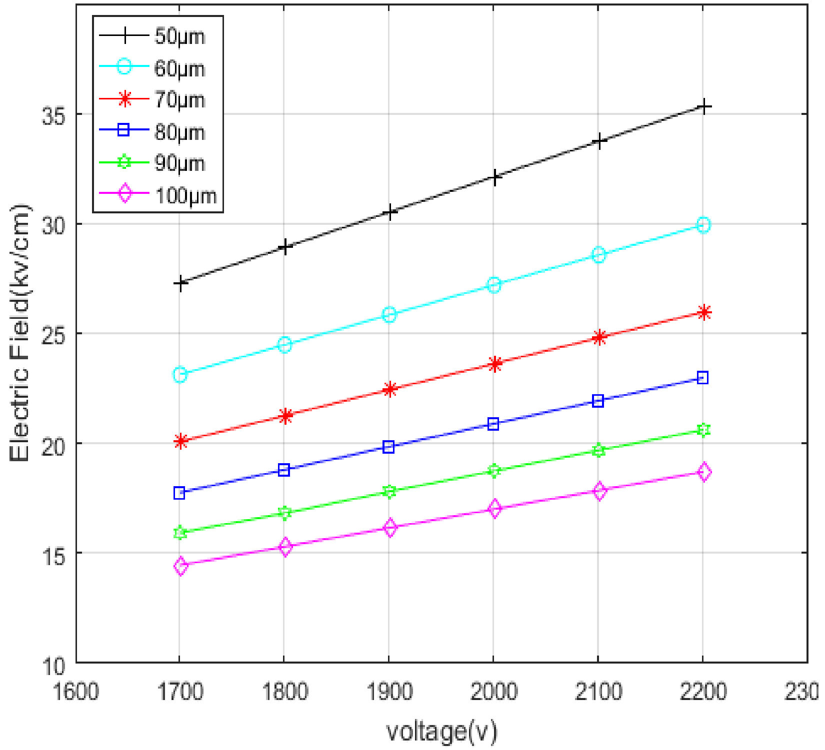
Backup

Garfield++ simulation

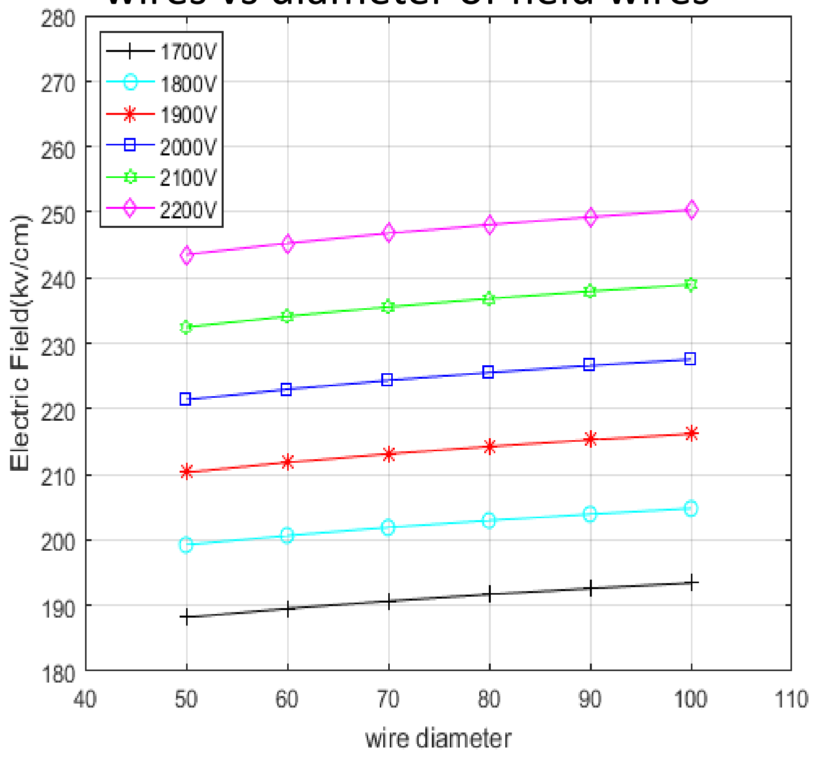
Gain vs HV



Electric field on the surface of field wires vs HV



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



Material parameters in FEA

yield strength of 7075 aluminum:505MPa

Data

	Young's Modulus	Poisson's Ratio
1	71700000000	0.33

Density of CF 1.6

Data

	E1	E2	Nu12	G12	G13	G23
1	320000000000	7000000000	0.29	4200000000	4200000000	2700000000

CF parameter

Data

	Ten Stress Fiber Dir	Com Stress Fiber Dir	Ten Stress Transv Dir	Com Stress Transv Dir	Shear Strength	Cross-Prod Term Coeff	Stress Limit
1	2000000000	600000000	22000000	100000000	50000000	0	0

Carbon Fiber Material parameter

性能	东丽M55J复合材料	测试标准
	室温	
0度拉伸强度，Mpa	2000	ASTM D3039
0度拉伸模量，GPa	320	
泊松比	0.29	
90度拉伸强度，Mpa	22	
90度拉伸模量，GPa	7.0	
弯曲强度，Mpa	1000	ASTM D7264
弯曲模量，GPa	230	
0度压缩强度，Mpa	600	ASTM D6641
0度压缩模量，GPa	300	
90度压缩强度，Mpa	100	
90度压缩模量，GPa	6.5	
ILSS，Mpa	50	ASTM D2344
面内剪切强度，Mpa	50	ASTM D3518
面内剪切模量，GPa	4.2	

M55J CF

FEA for different thick end plates

Thickness of end plate (mm)	Material budget (X_0)	Max Deformation (mm)	Max Stress （MPa）
30	33.7%	2.0	16.7
25	28.1%	2.5	20.9
20	22.5%	3.4	27.1