Drift chamber towards CEPC Reference TDR

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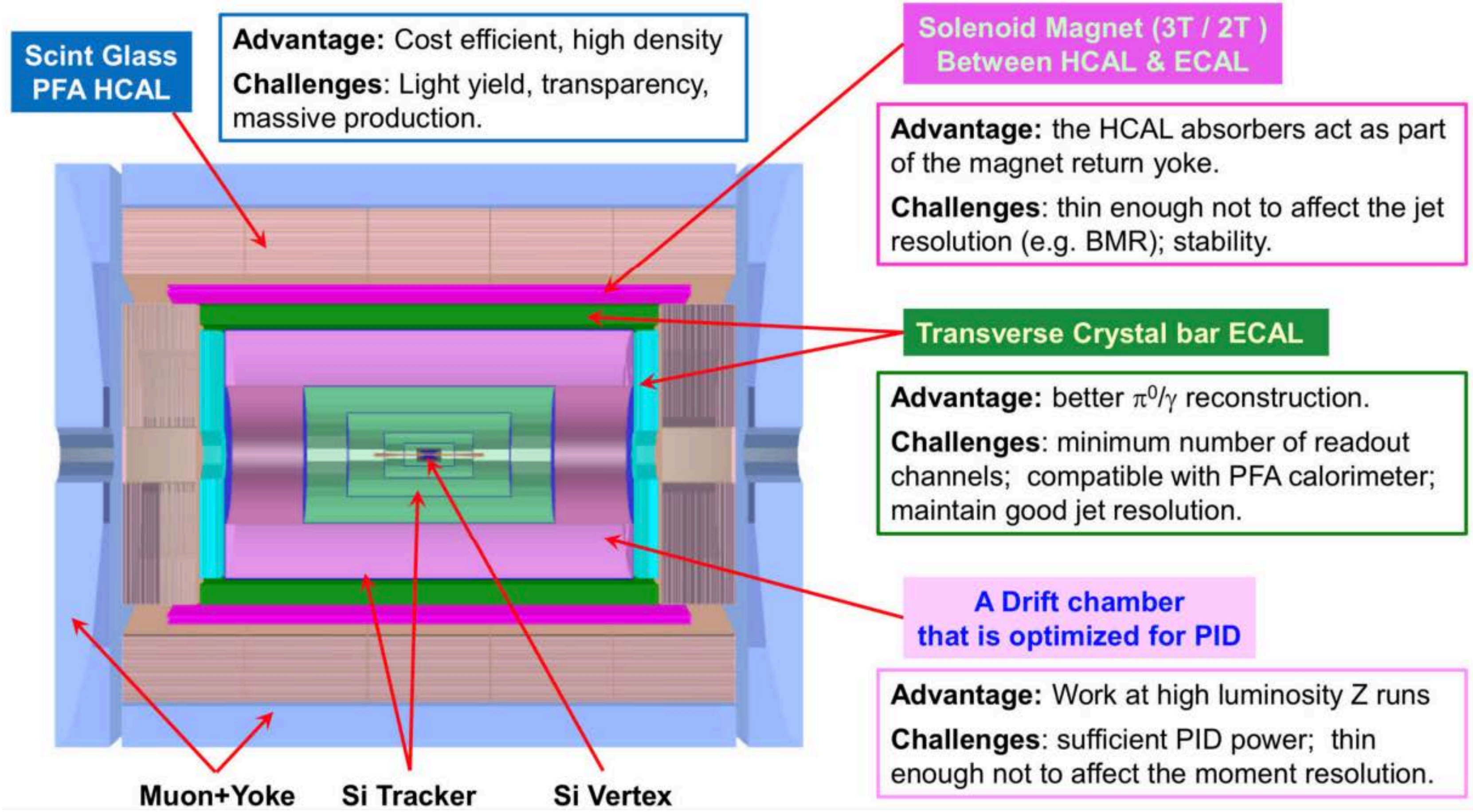
On behalf of DC group

2024.4.2

Outline

- **Introduction**
- **Performance study and prototype test**
- **Mechanical design and FEA**
- **Electronics scheme**
- **Summary**

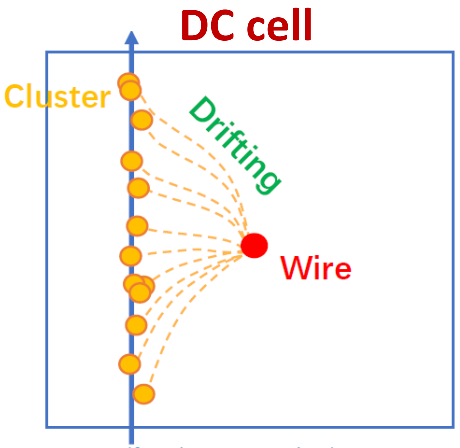
Drift Chamber in CEPC 4th conceptual detector



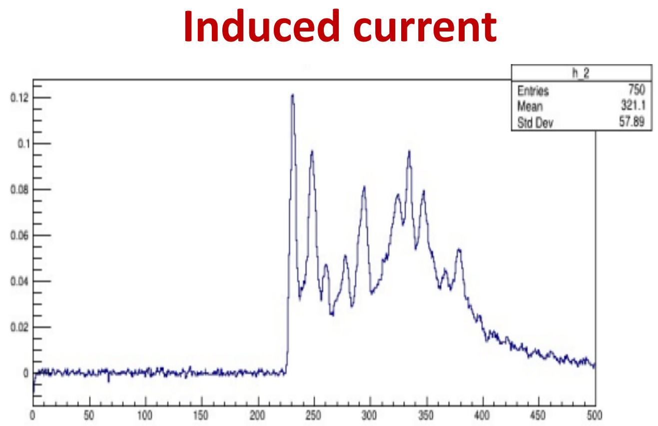
- The drift chamber optimized for PID with cluster counting technique
- Require better than 3σ separation power for K/π with momentum up to 20GeV/c
- Benefits tracking and momentum measurement

Ionization measurement with dN/dX

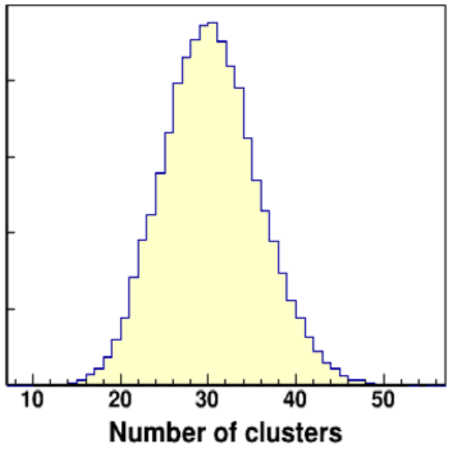
- Measure number of clusters over the track, the number of clusters corresponds to the number of the primary ionization
- Yield of primary ionization is Poisson distribution
- To eliminate the effects of secondary ionization, dN/dx is based on peak finding and clusterization



(for demonstration)



Peak finding
+clusterization



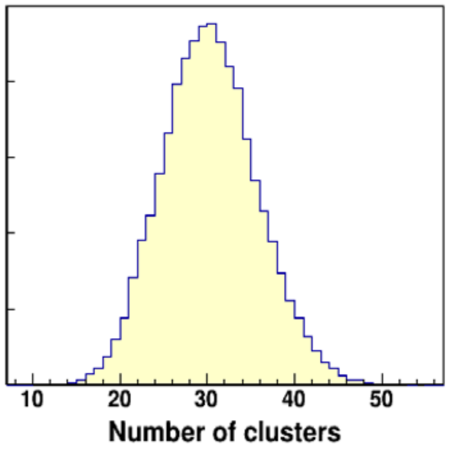
Primary ionization

dN/dx vs dE/dx

dN/dx

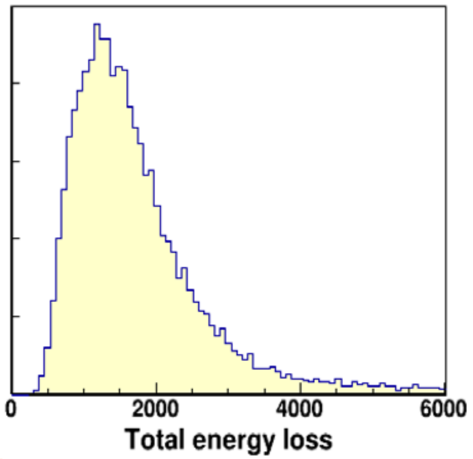
- Number of primary ionization clusters per unit length
- Poisson distribution
- Small fluctuation

Cluster counting technique

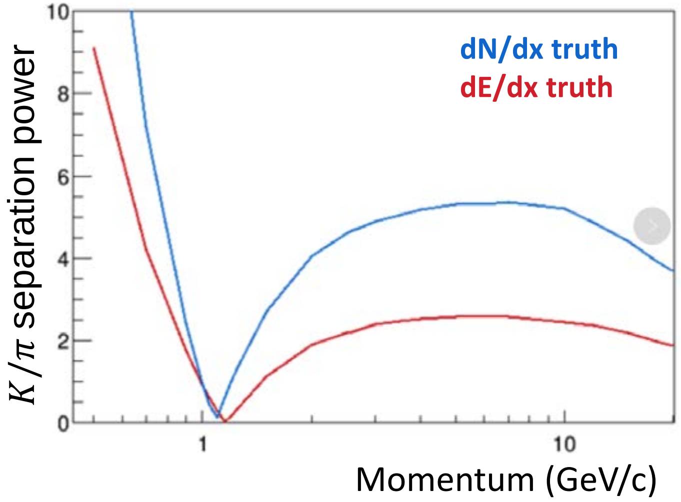


dE/dx

- 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)

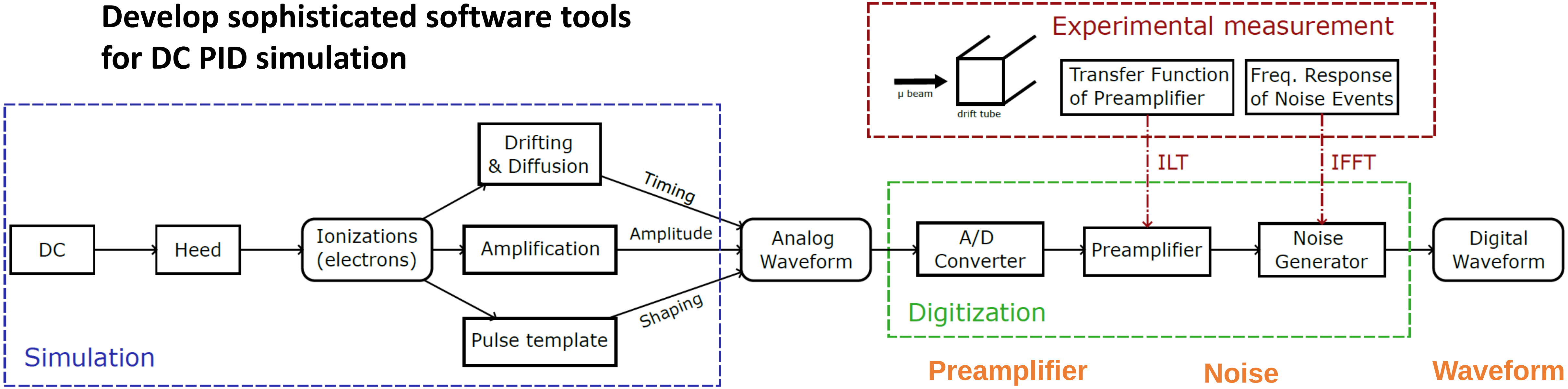
Key issues with dN/dx measurement

- 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
- Waveform test
  - Fast and low noise electronics
- dN/dx reconstruction algorithm
  - Identifying primary and secondary ionization signals
  - Reducing noise impacts

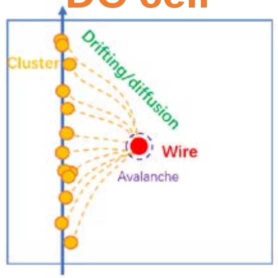
Performance study

Waveform-based full simulation

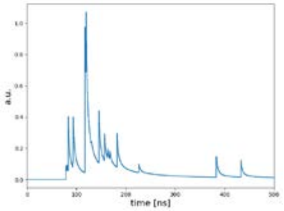
Develop sophisticated software tools for DC PID simulation



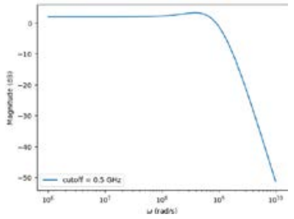
DC cell



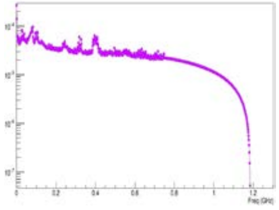
Induced signal



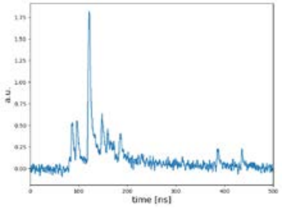
Preamplifier



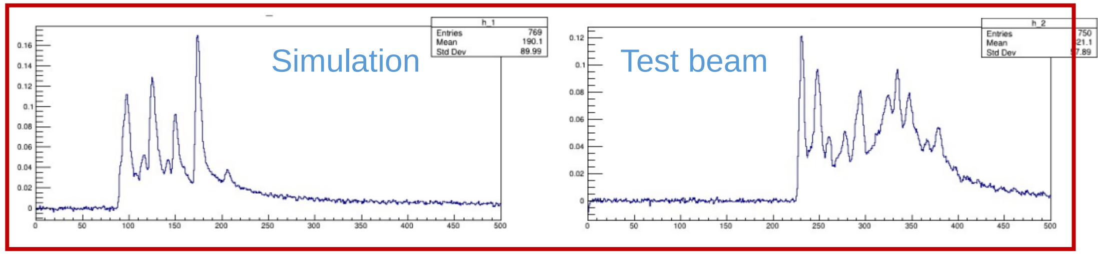
Noise



Waveform



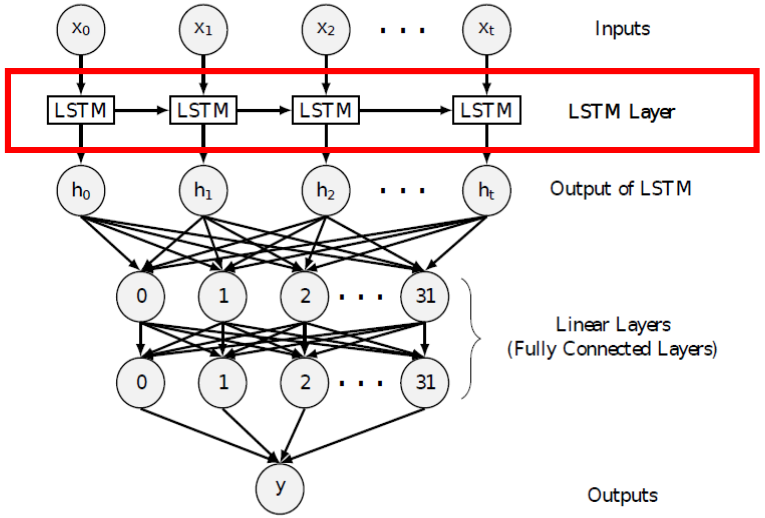
Tuned MC is comparable to data

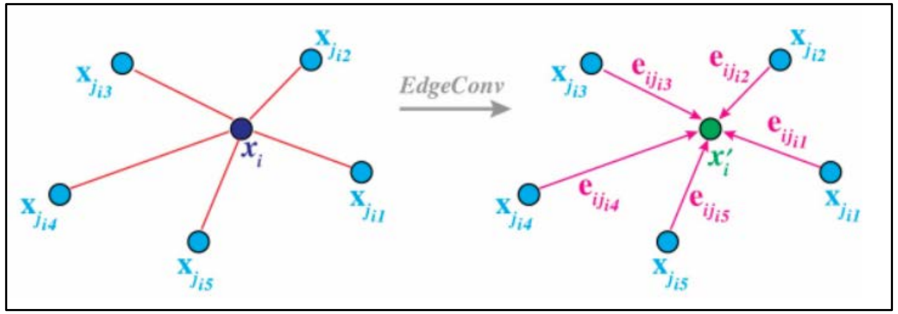


Machine learning reconstruction

- LSTM-based peak finding and DGCNN-based clusterization

NN architecture





arXiv: 1801.07829

Long Short-Term Memory (LSTM)

- A specified recurrent neural network (RNN) that deals with the vanishing gradient problem
- Can handle long sequences efficiently

LSTM-based peak finding

- Waveform as sliding windows
- Binary classification of signals and noises

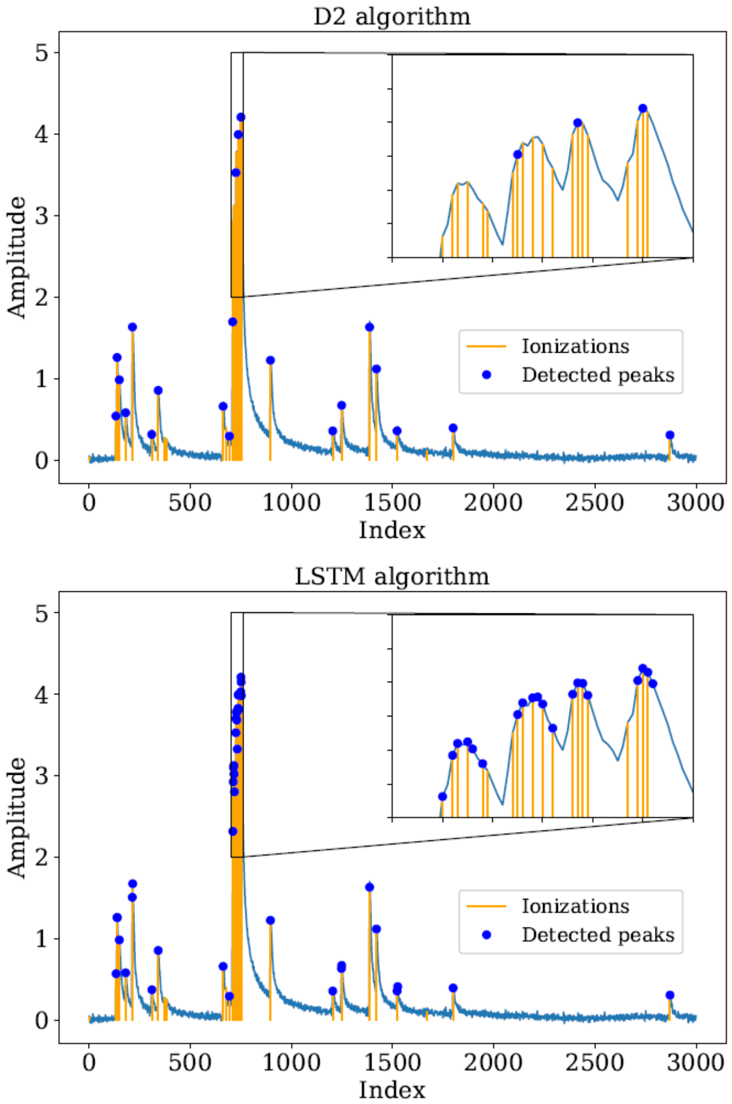
Dynamic Graph CNN (DGCNN)

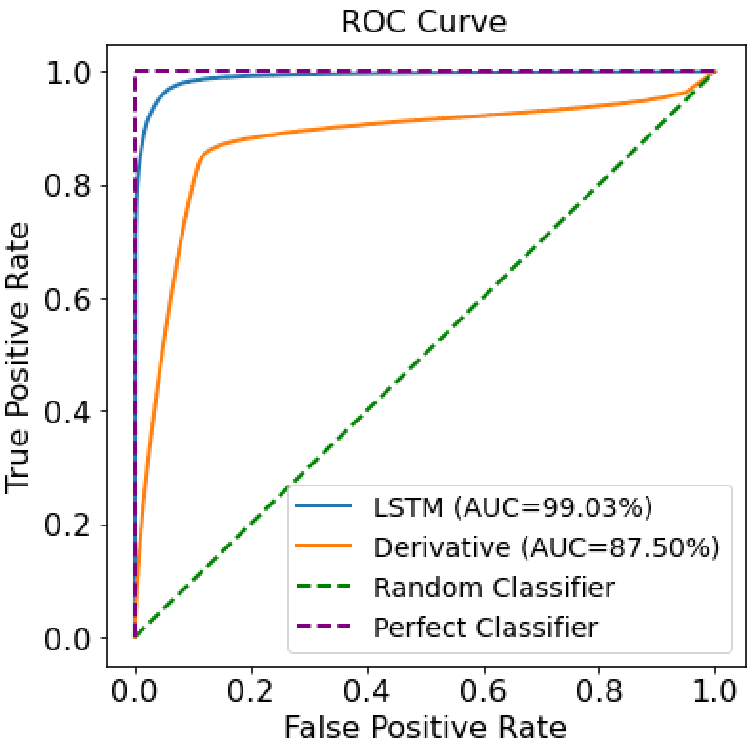
- A specified graph neural network (GNN) that operates dynamically on graphs computed in each layer of the network
- The DGCNN incorporates local information and stacked to learn global shape properties, which is very suited for clusterization

DGCNN-based clusterization

- Peak timing as the node feature. Edges are initially connected by timing similarity.
- Binary classification of primary and secondary electrons

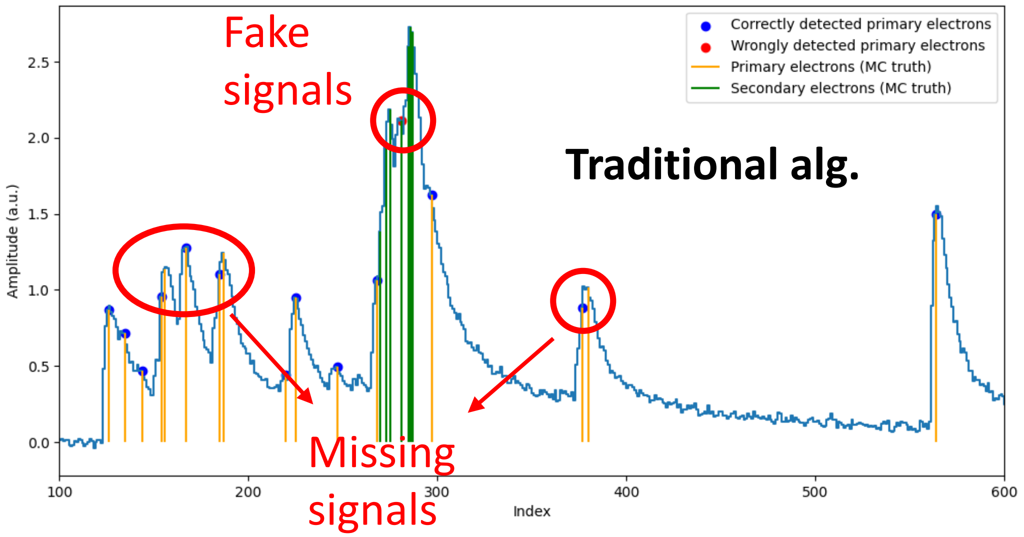
Peak finding results

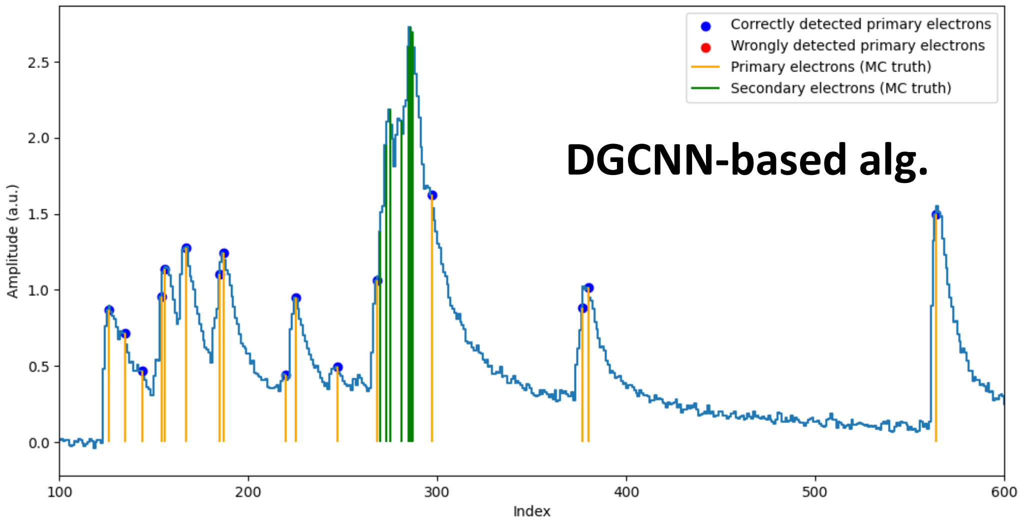


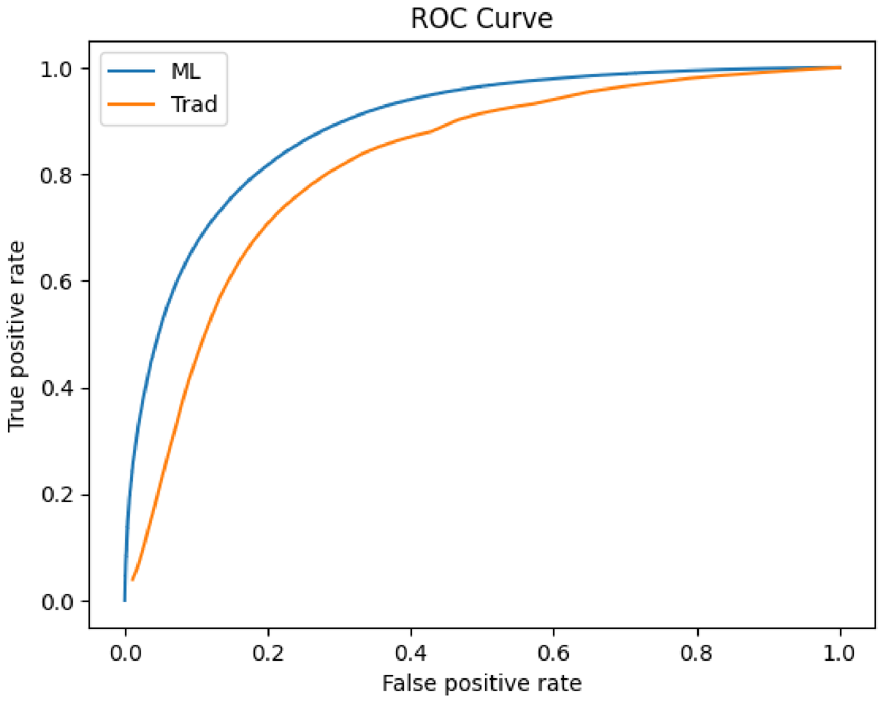


- The LSTM-based model is a more powerful classifier
- The efficiency is higher than the derivative-based algorithm, especially for the pile-up recovery

Clusterization results



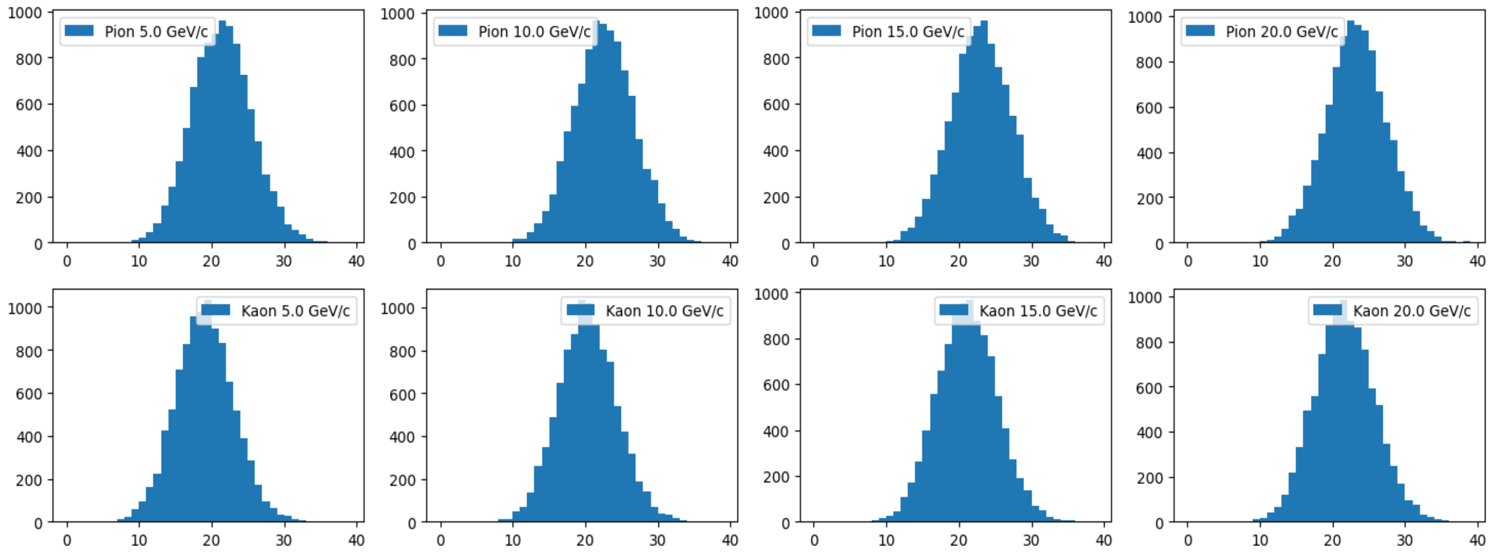


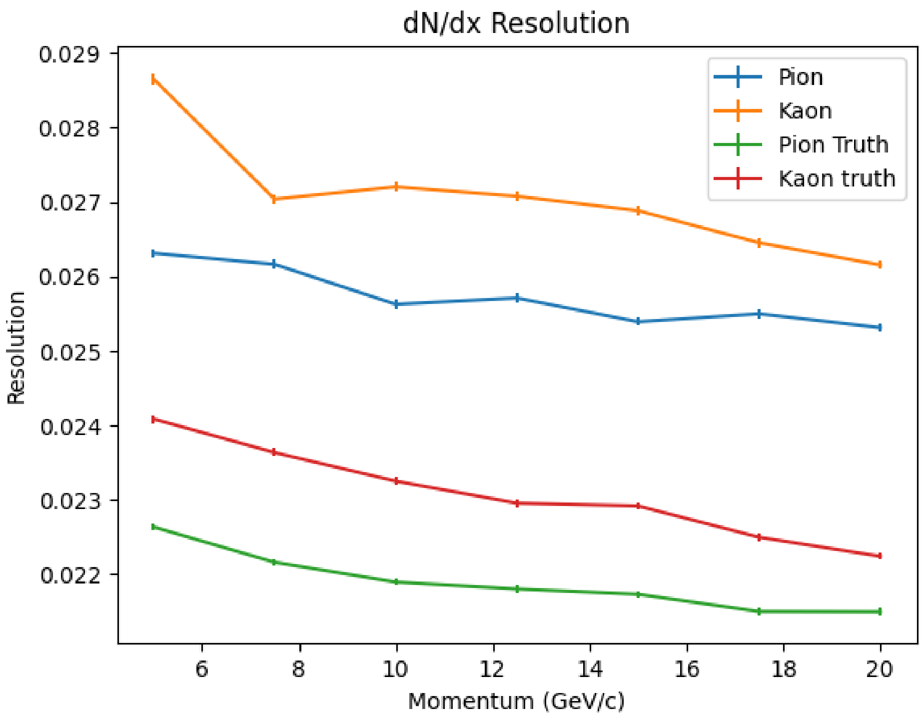


- The DGCNN-based model is a more powerful classifier
- The efficiency is higher, and the fake rate is lower

- ~10% improvement with ML (equivalent to a detector with 20% larger radius)

dN/dx Resolution

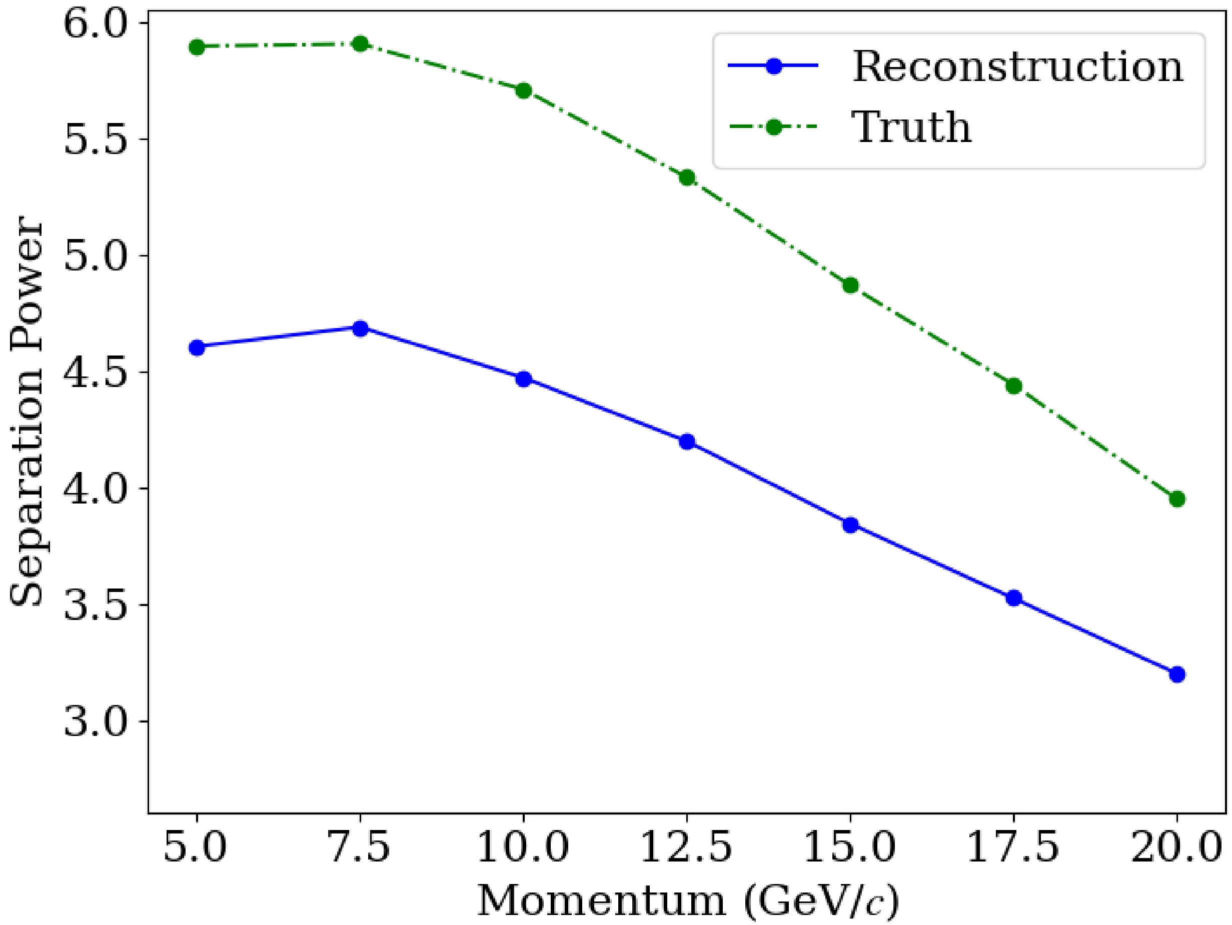




The reconstructed n_{cls} distributions are Gaussian-shaped

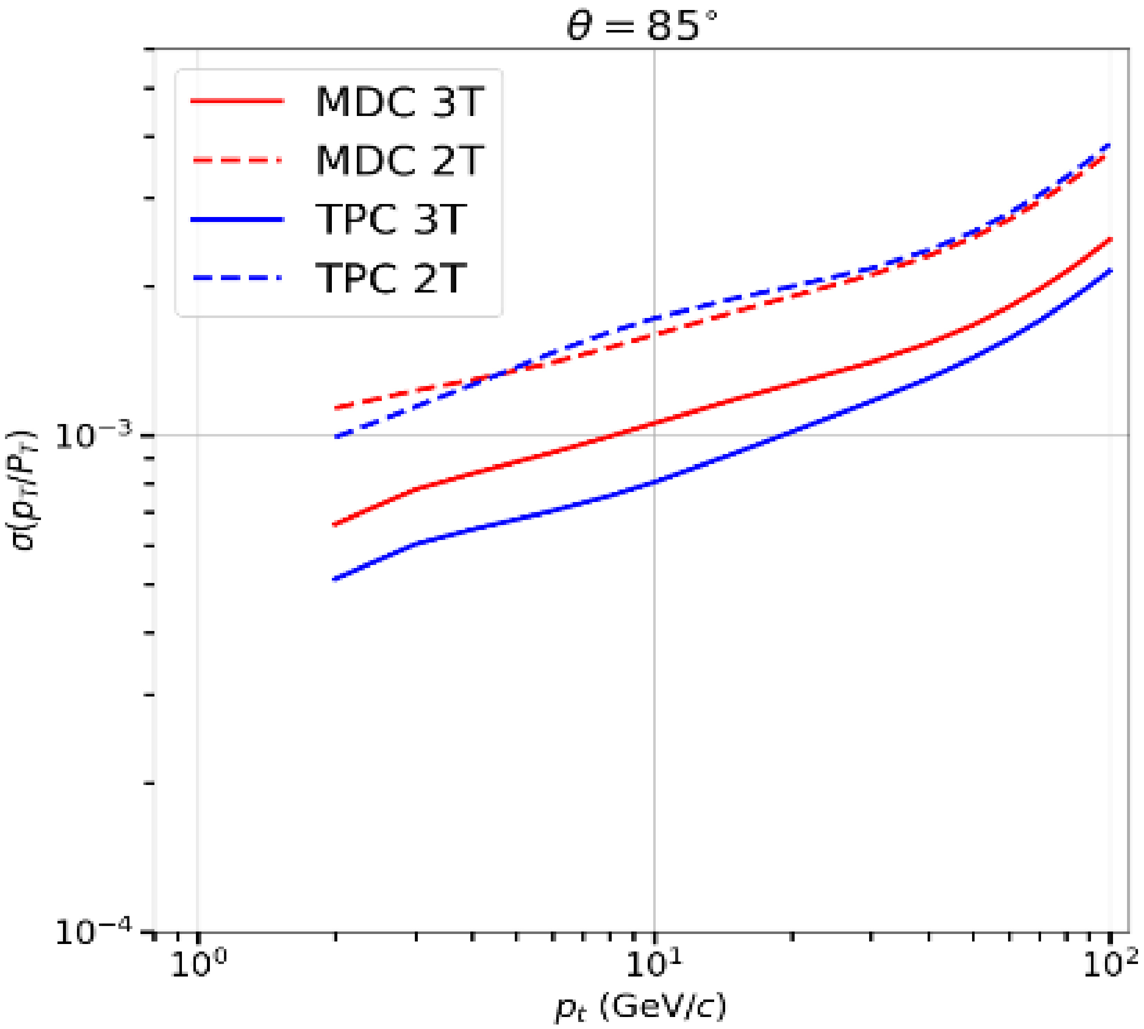
- dN/dx resolution: 2.5%-2.6% for pion
- 2.6%-2.7% for Kaon

PID performance



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

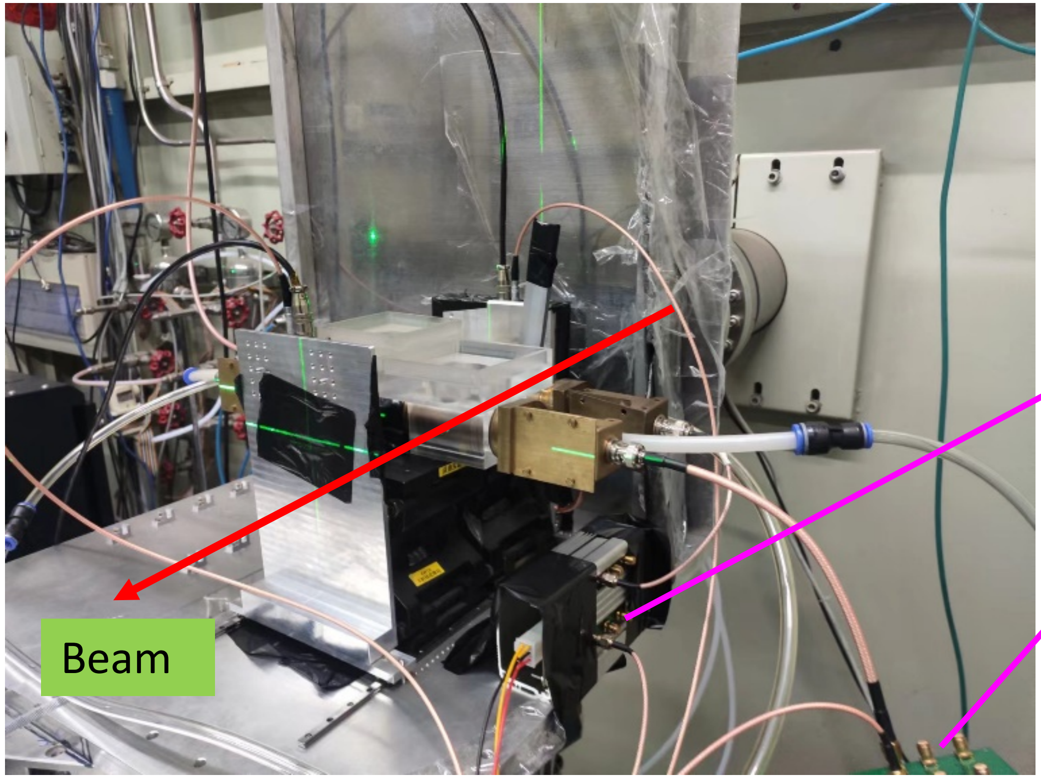
Momentum Resolution

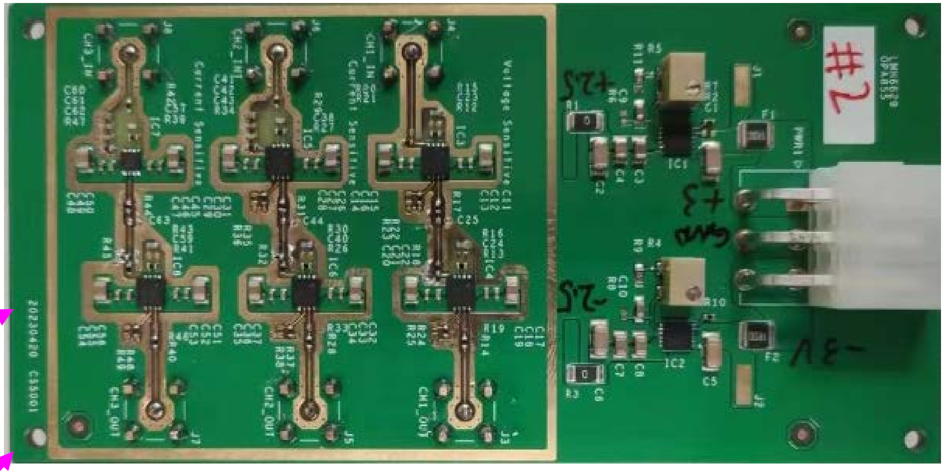


$\sigma(1/pT) = a \pm b/pT$

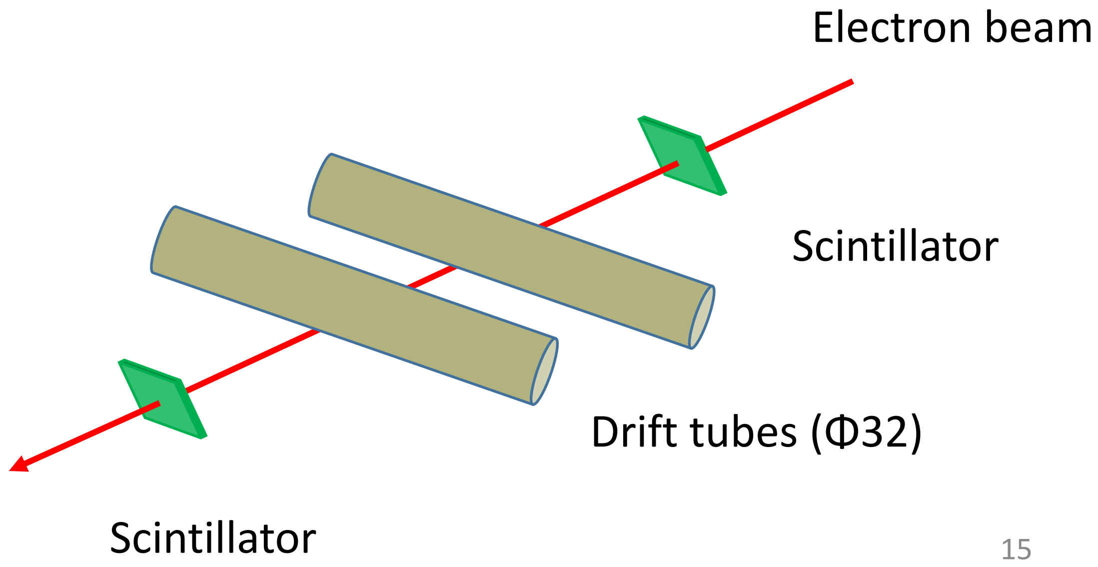
	Higgs	Z-pole
a (1/GeV)	2.1×10^{-5}	3.2×10^{-5}
b	0.77×10^{-3}	1.16×10^{-3}

Beam test with detector prototype (IHEP)

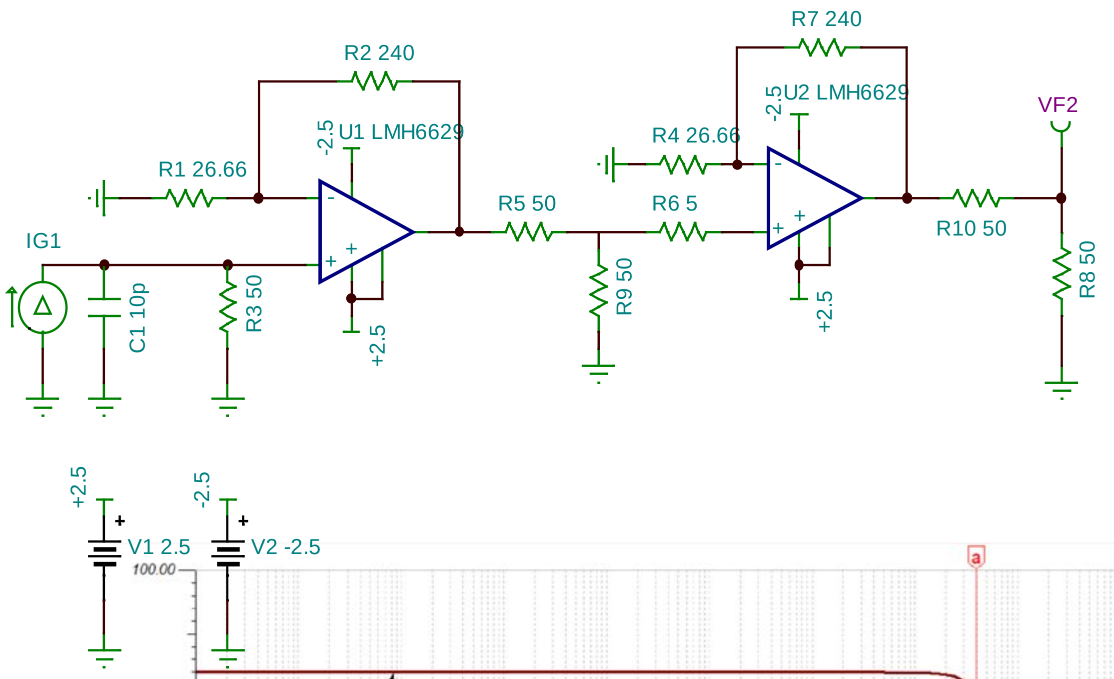


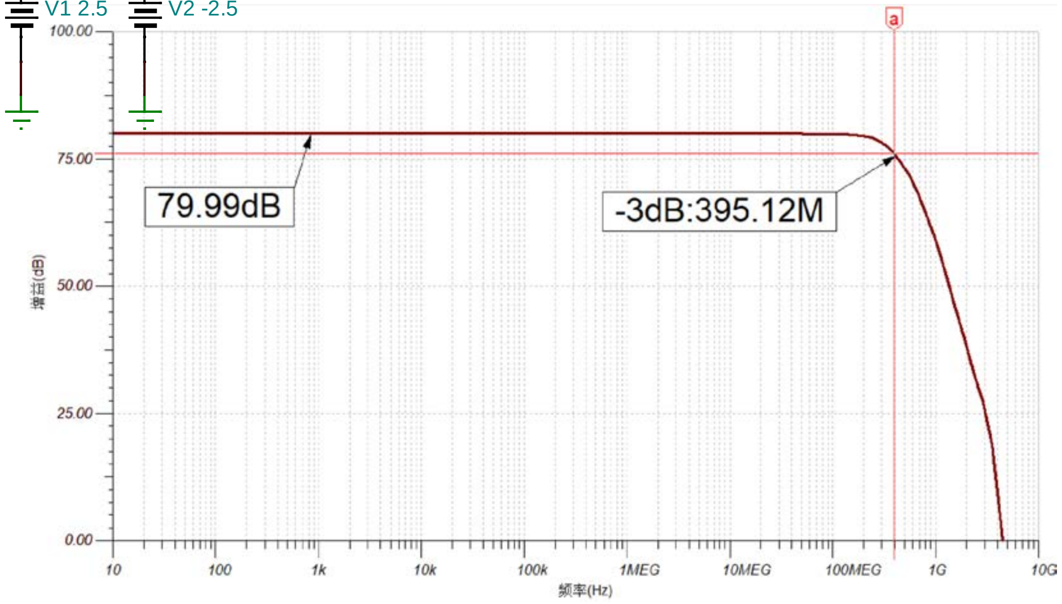


- Two drift tubes + preamps + ADC (1GHz)
- The system was tested with electron beam at IHEP

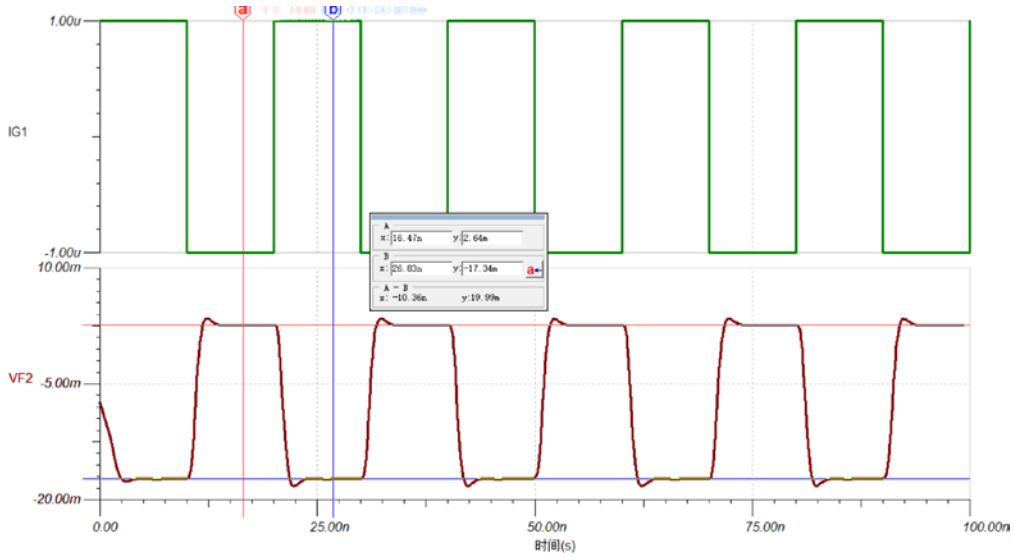


Preamplifier





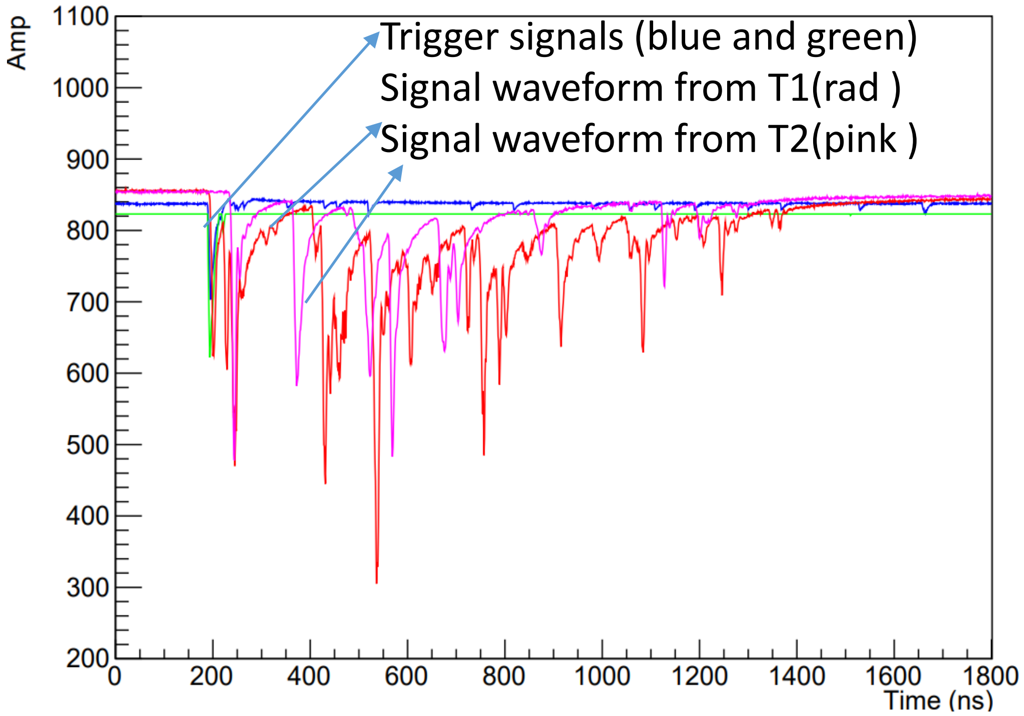
Gain vs frequency

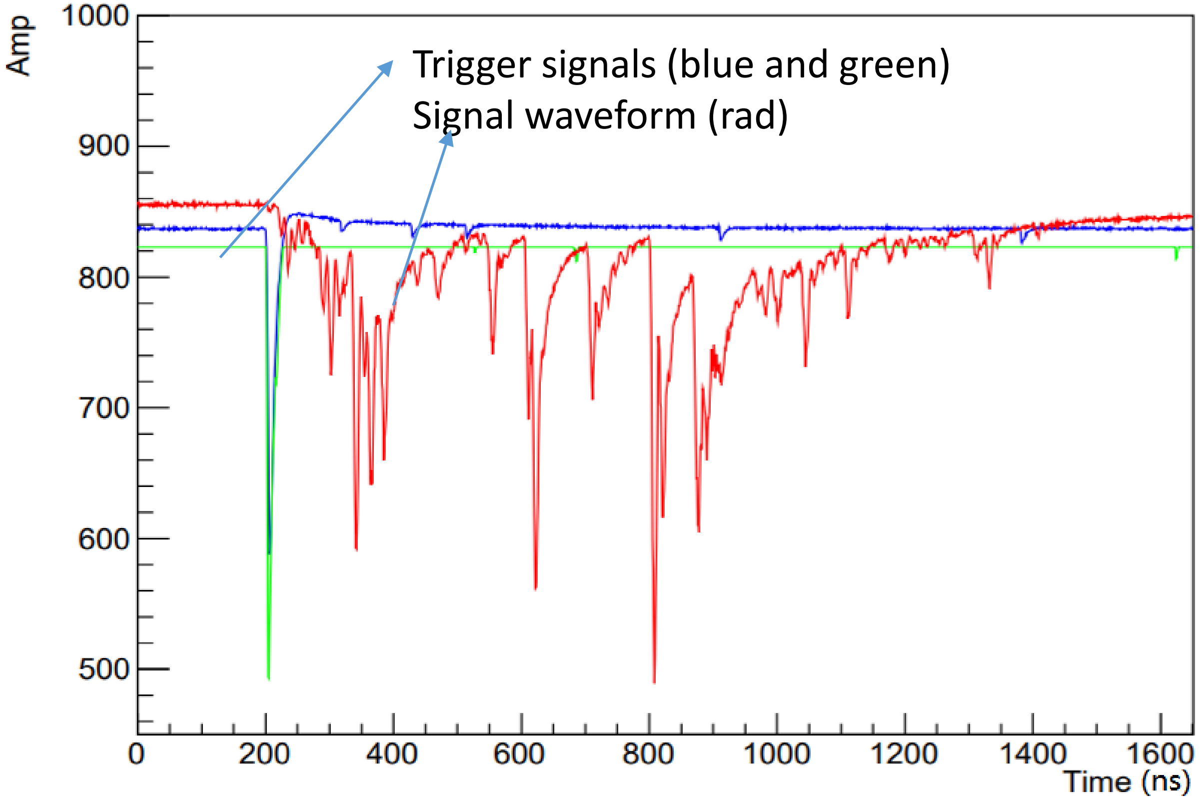


waveform simulation at 10pF

Typical Waveform

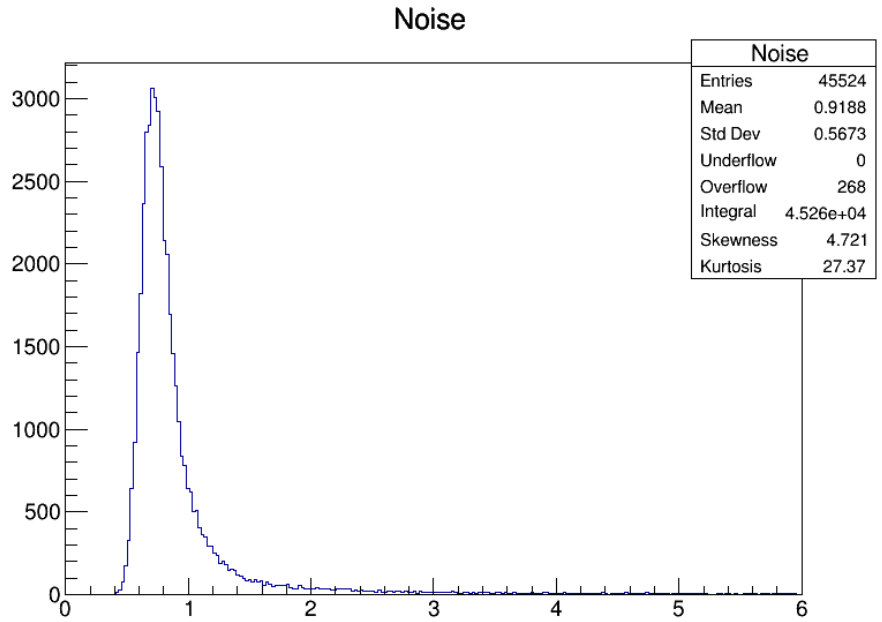
- He: iC_4H_{10} = 90 : 10
- Digitizer: DT5751
  - Sampling rate: 1GHz
  - Four channels, two for scintillators, two for drift tubes

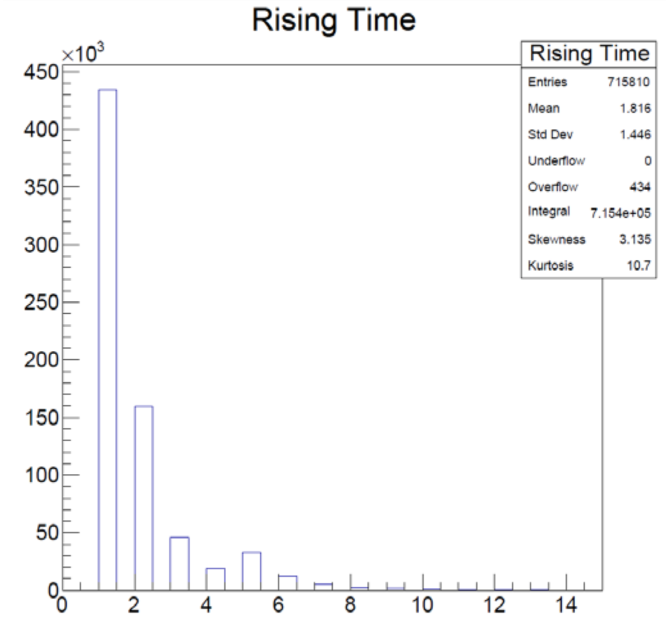


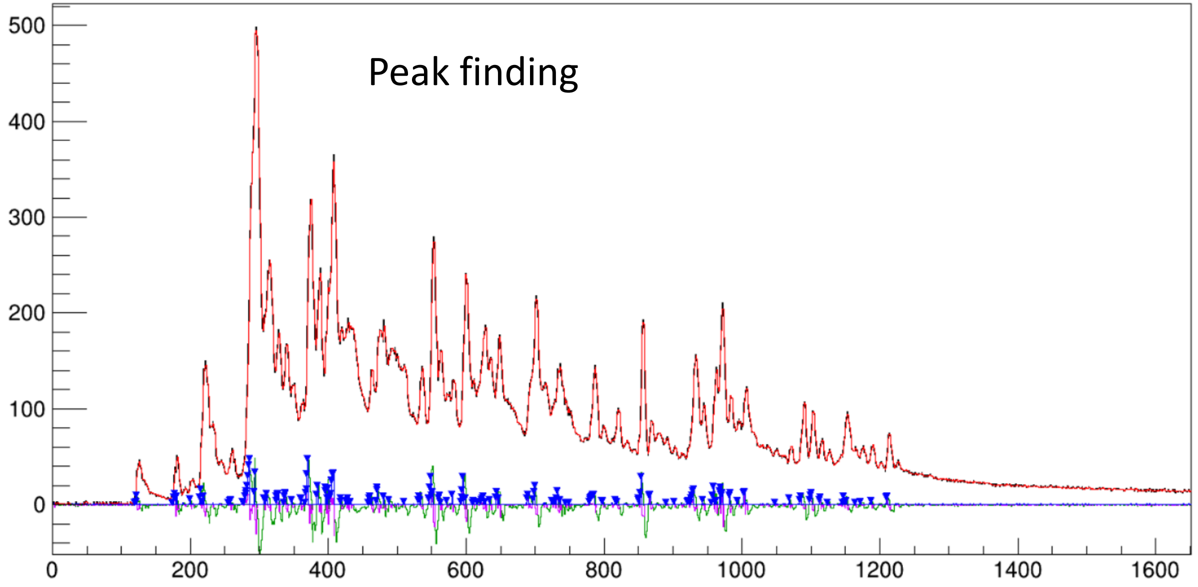


Preliminary analysis

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







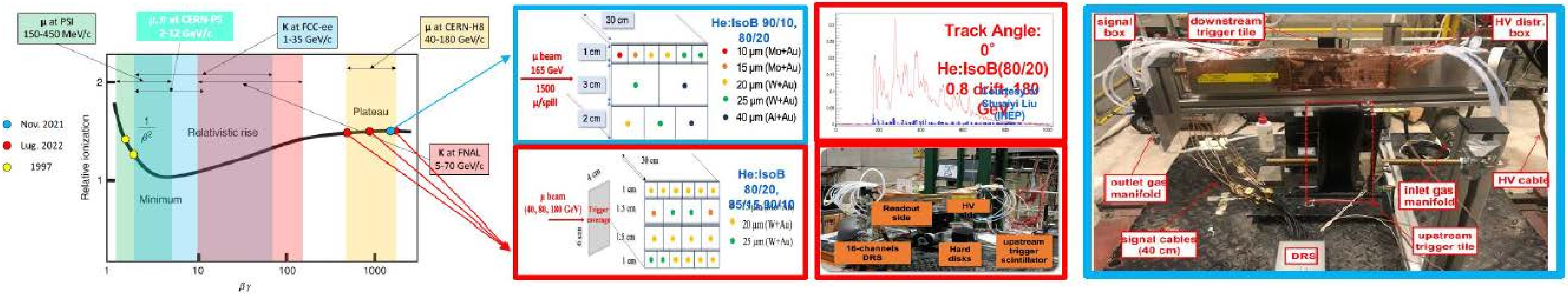
Collaboration with Italy group

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 (βγ = 10-14) to fully exploit the relativistic rise.

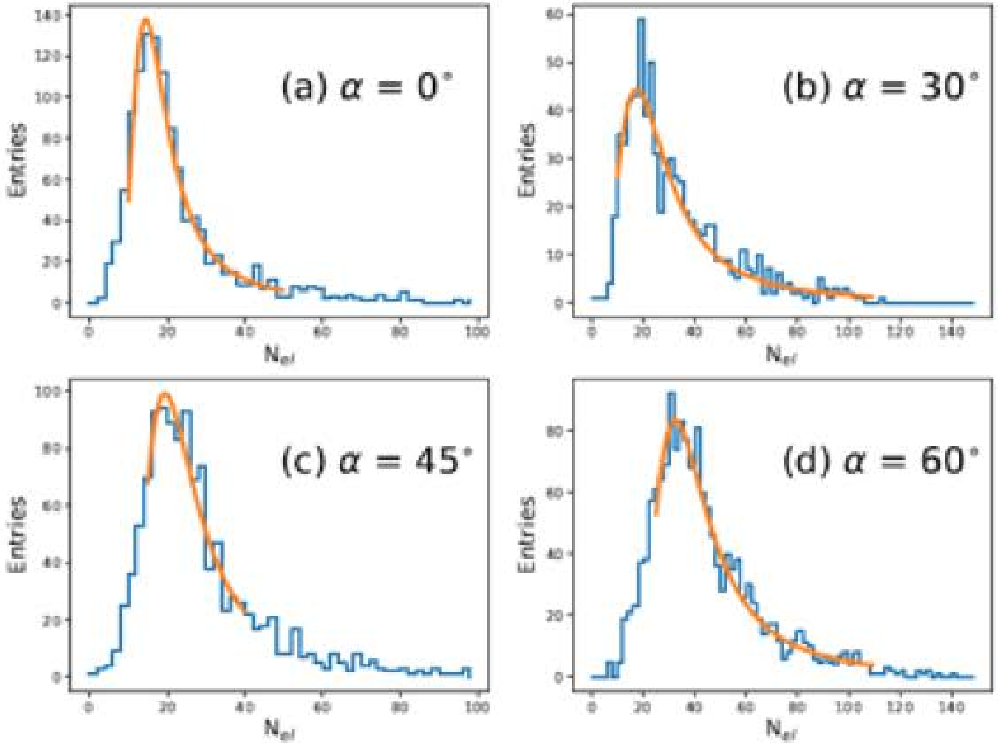
Contributions from IHEP group:

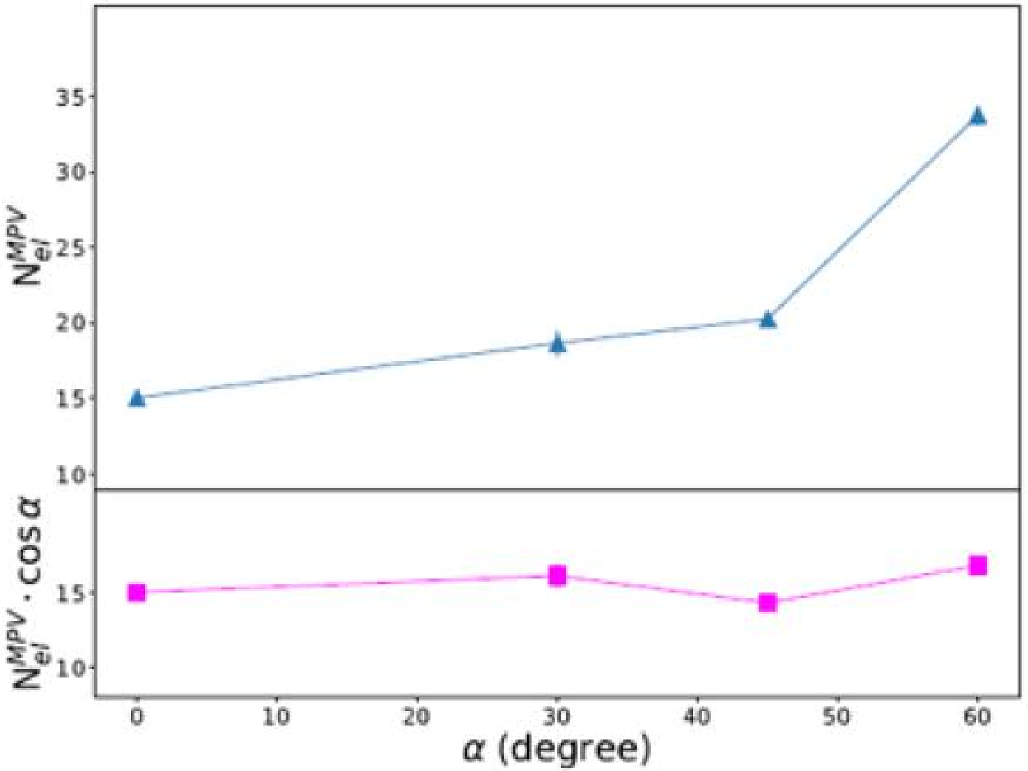
- Participate data taking and collaboratively analyze the test beam data
- **Develop the machine learning reconstruction algorithm**



[See Nicola De Filippis's talk at the CEPC Workshop for details]

Data analysis with ML reconstruction

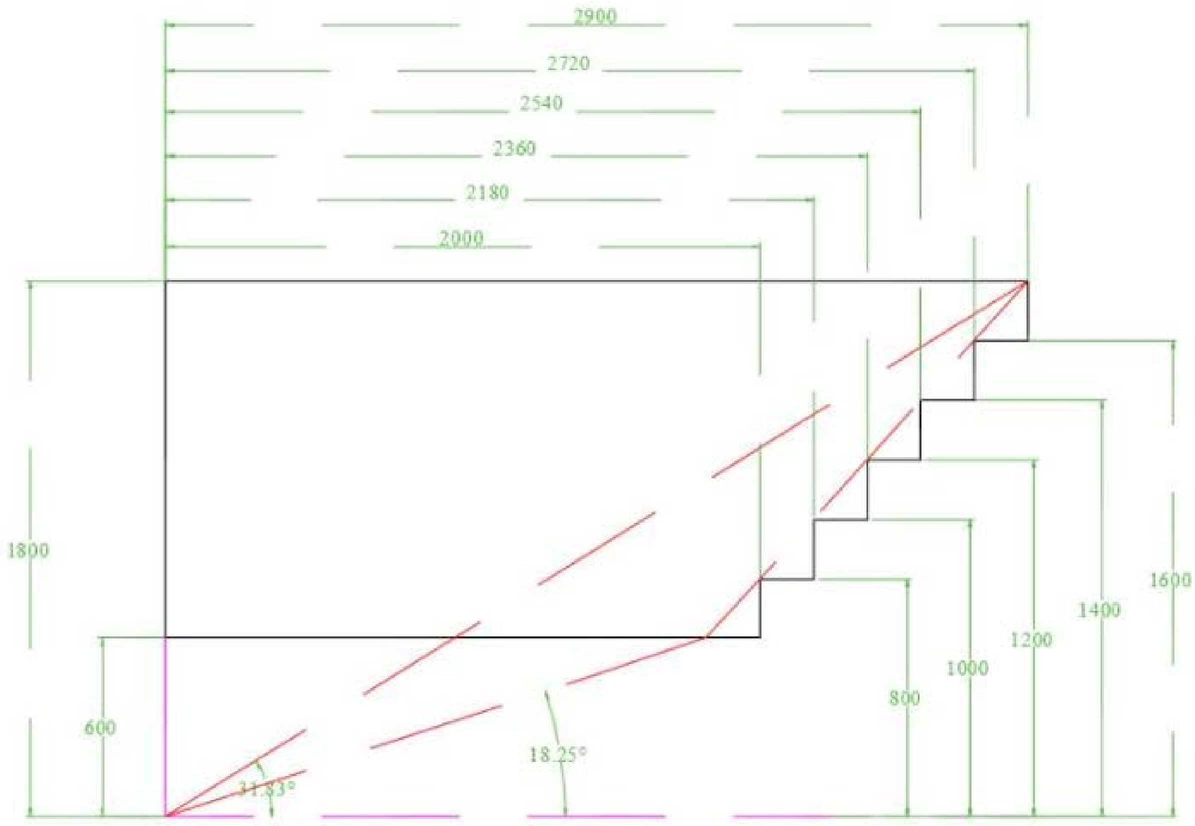


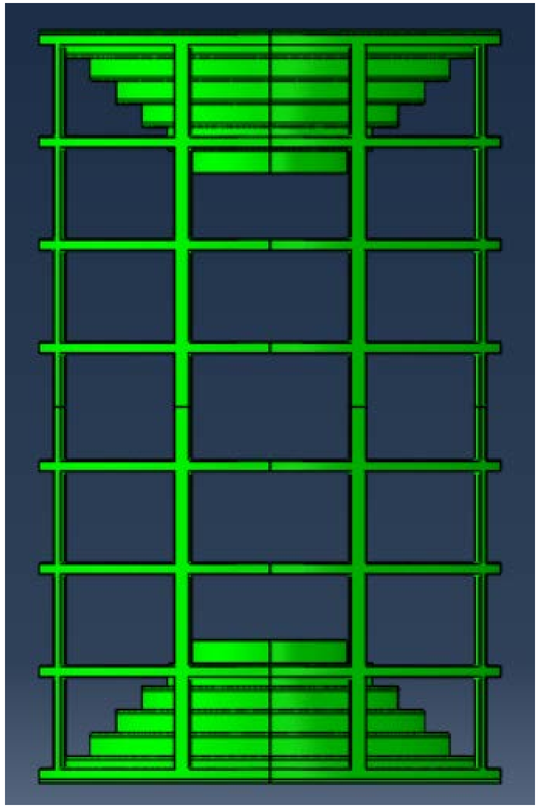


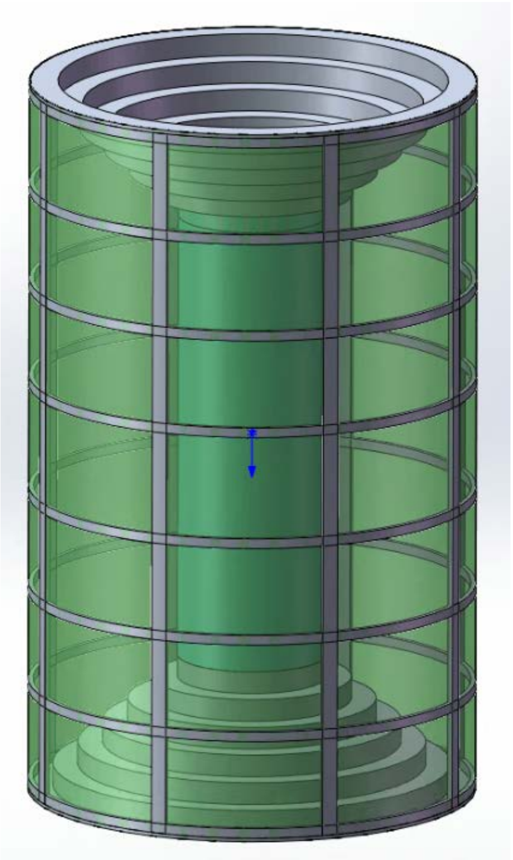
- Multi-waveform results for samples in different angles
- The algorithm is stable w.r.t. track length

Mechanical design and FEA

Overall Design (preliminary)



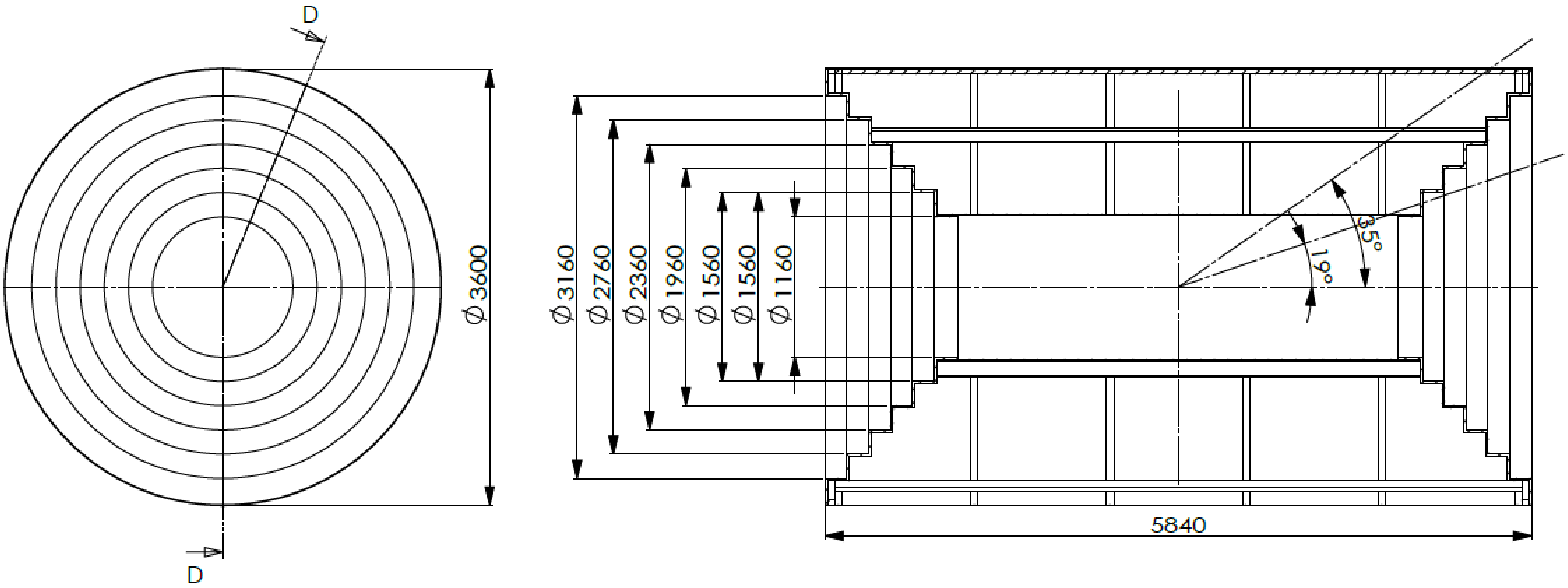




CF Frame structure： 8 longitudinal hollow beams + 8 annular hollow beams + inner CF cylinder and outer CF cylinder

- 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 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:

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

Loads

Wire Tension

	cell number/step	length	Sense wire tension(g) /cell	Field wire tension(g) /cell	Sense wire tension (kg)	Field wire tension (kg)	total tension(kg) /step
	2684	4000	43.29	66.52	116.19	535.59	651.78
	3452	4360	51.43	79.03	177.55	818.41	995.95
	4220	4720	60.28	92.62	254.37	1172.51	1426.88
	4988	5080	69.82	107.29	348.27	1605.36	1953.63
	5756	5440	80.07	123.03	460.87	2124.39	2585.27
	6524	5800	91.02	139.85	593.79	2737.07	3330.85
total	27623				1951	8993	10944

yield strength of 7075 aluminum:505MPa

	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

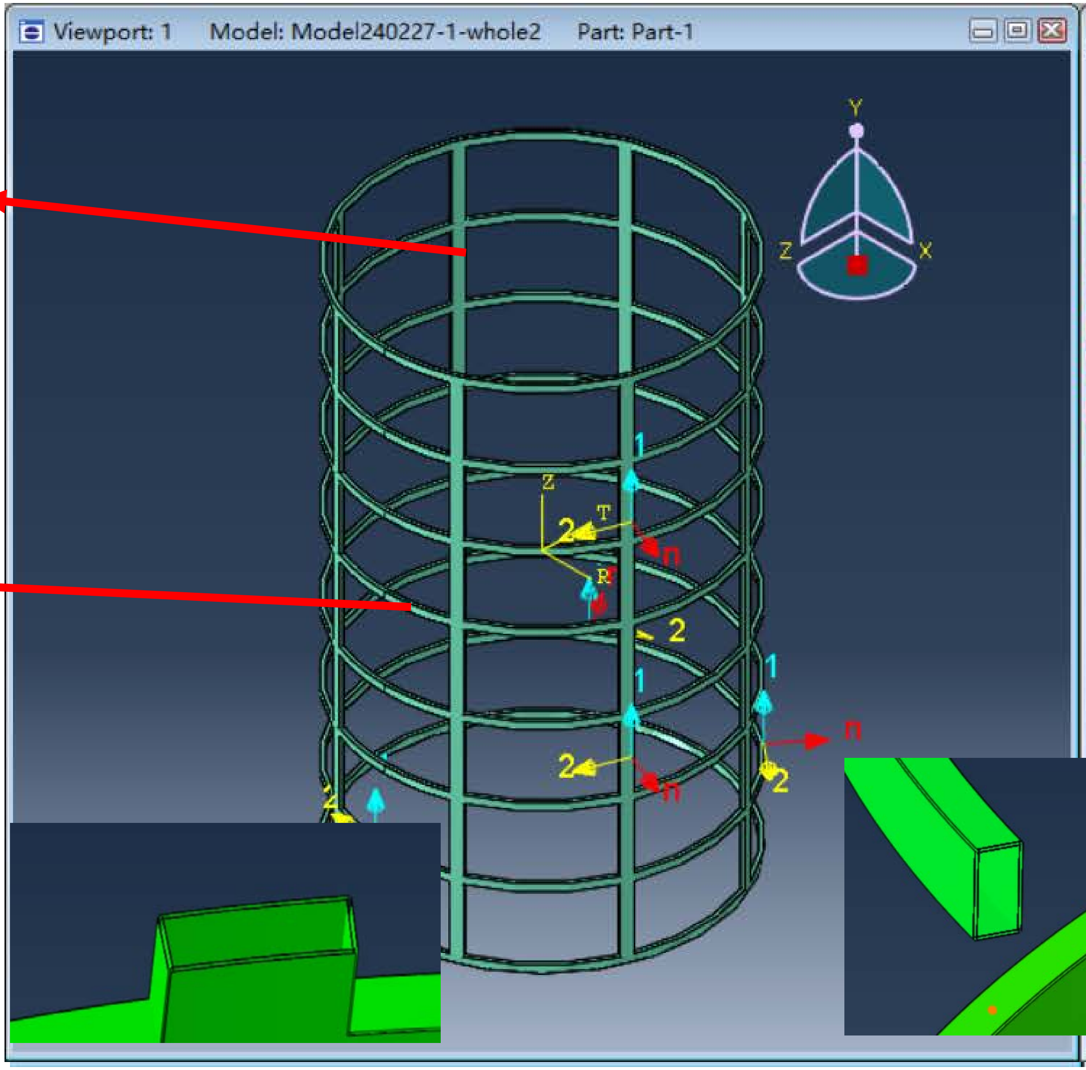
性能	东丽M55J复合材料	测试标准
	室温	
0度拉伸强度，Mpa	2000	ASTM D3039
0度拉伸模量，GPa	320	
泊松比	0.29	
90度拉伸强度，Mpa	22	
90度拉伸模量，GPa	7.0	
弯曲强度，Mpa	1000	ASTM D7264
弯曲模量，GPa	230	
0度压缩强度，Mpa	600	ASTM D6641
0度压缩模量，GPa	300	
90度压缩强度，Mpa	100	
90度压缩模量，GPa	6.5	
ILSS，Mpa	50	ASTM D2344
面内剪切强度，Mpa	50	ASTM D3518
面内剪切模量，GPa	4.2	

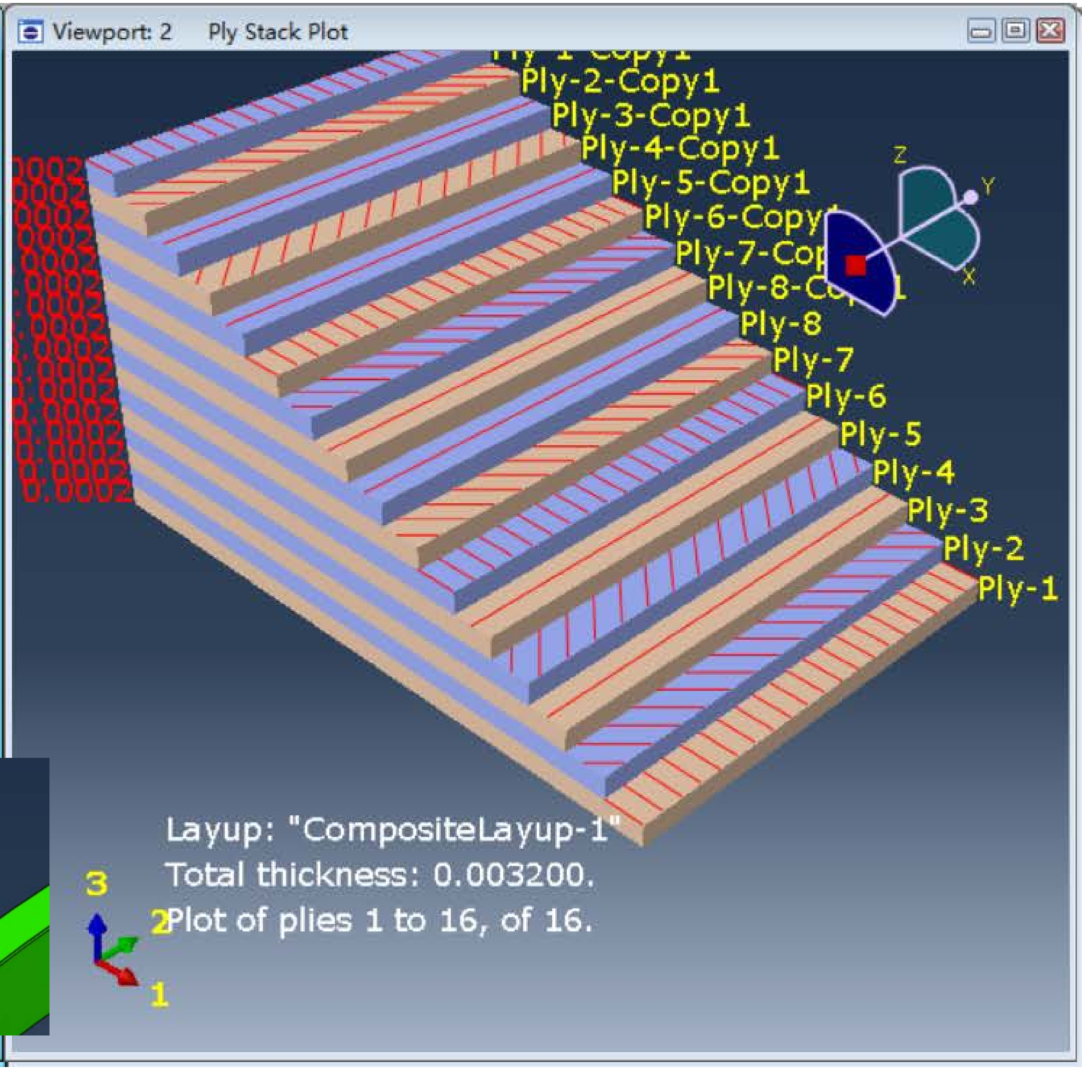
M55J CF

FEA

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

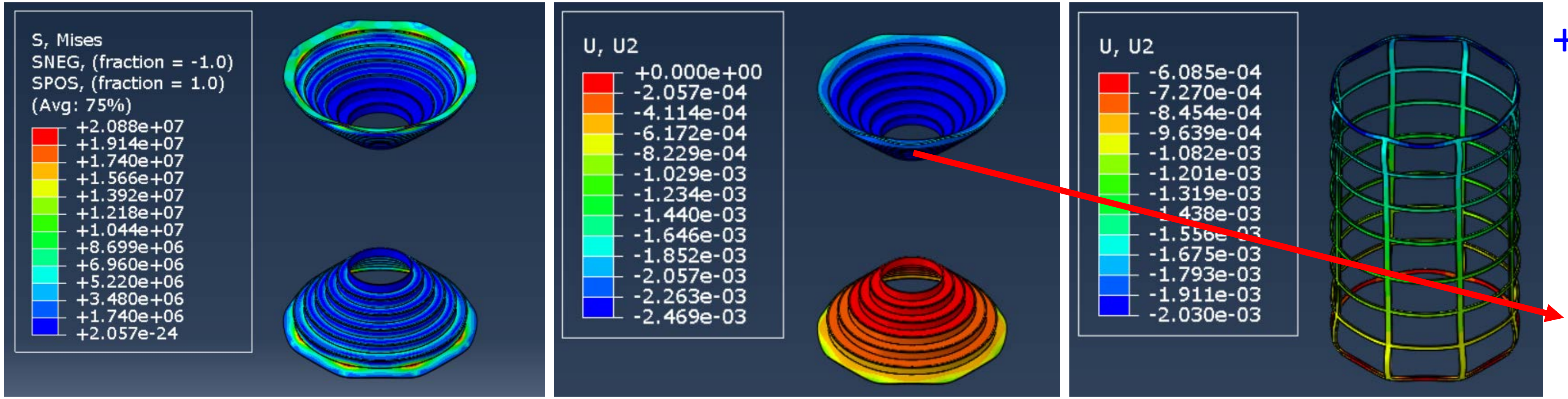
Cross section of annular HB：80*40mm
Thickness: 3.2mm
weight： 111kg





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

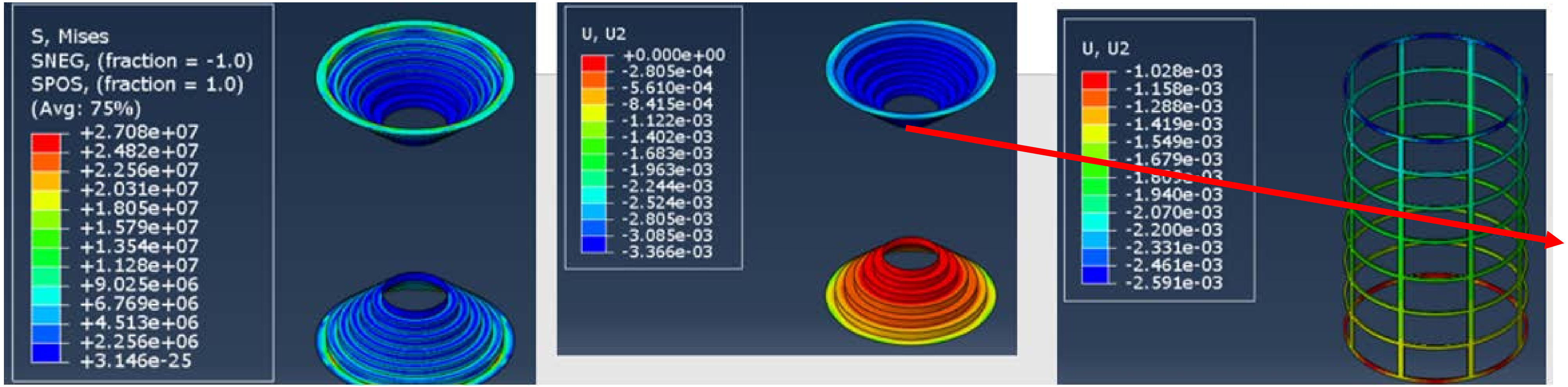
Results of FEA



Loads: Wire tension + Axial self weight

End plate thickness: 25mm

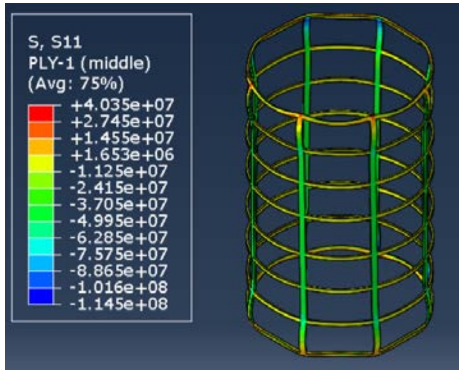
- Stress 20.9MPa,
- Endplate deformation 2.5mm,
- CF frame deformation 1.4mm

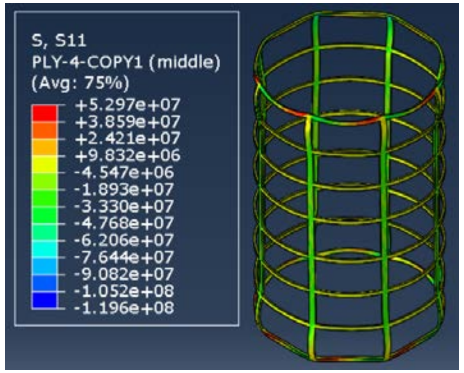


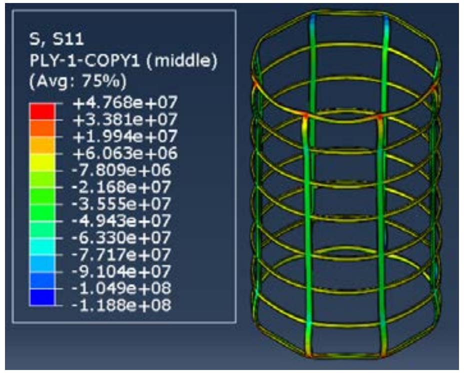
End plate thickness: 20mm

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

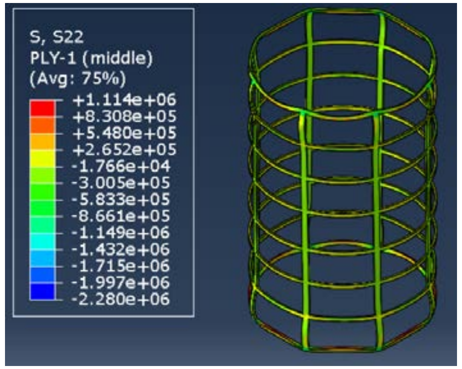
Results of FEA

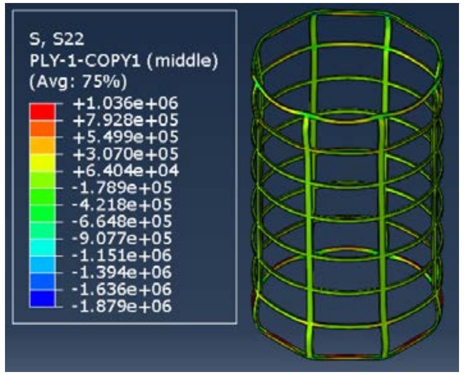




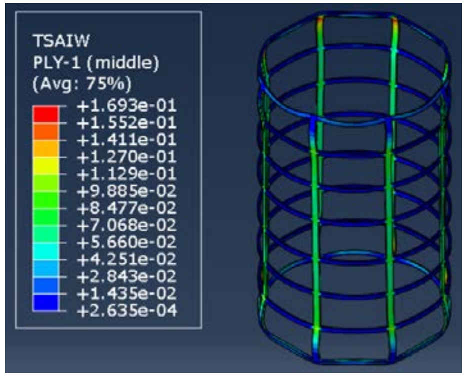


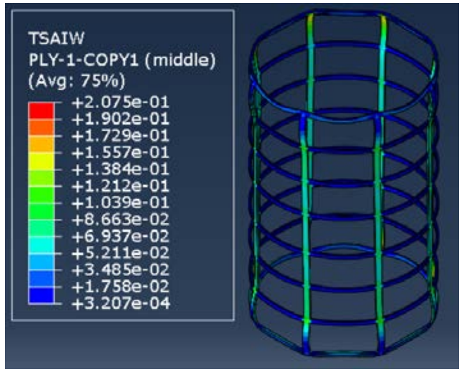
The maximum stress in the 0 degree direction of CF is 53MPa, located in the -4th layer





The maximum stress in the 90 degree direction of CF is 1.1 MPa, located in the first layer

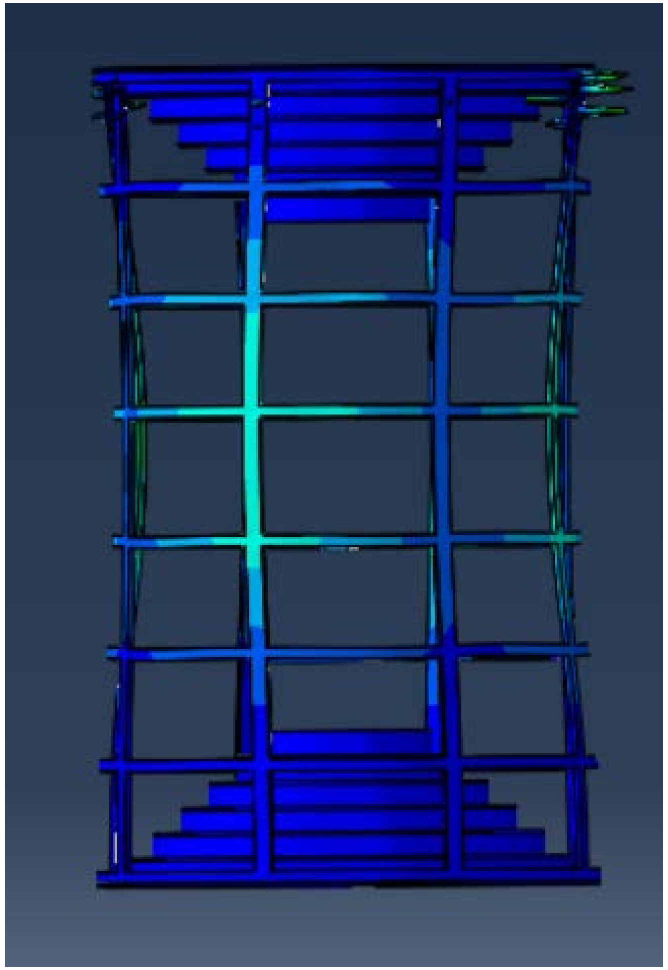




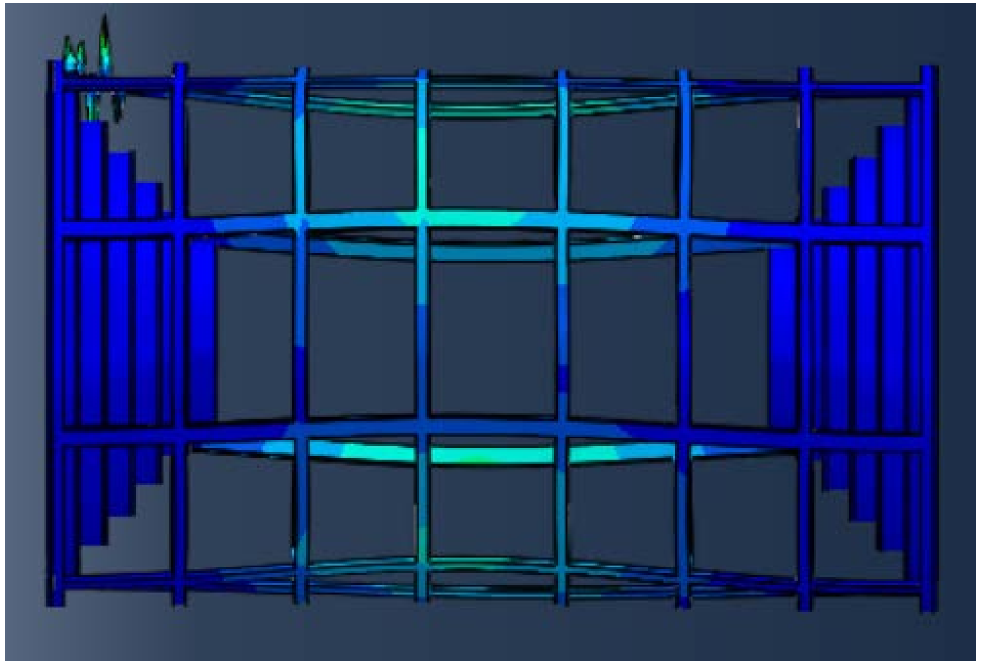
TSAIW： 0.21， located in the sixteenth layer

safety factor： ~ 5

Results of FEA



Vertical self weight
Buckling coefficient : ~12



Horizontal self weight
Buckling coefficient : ~14

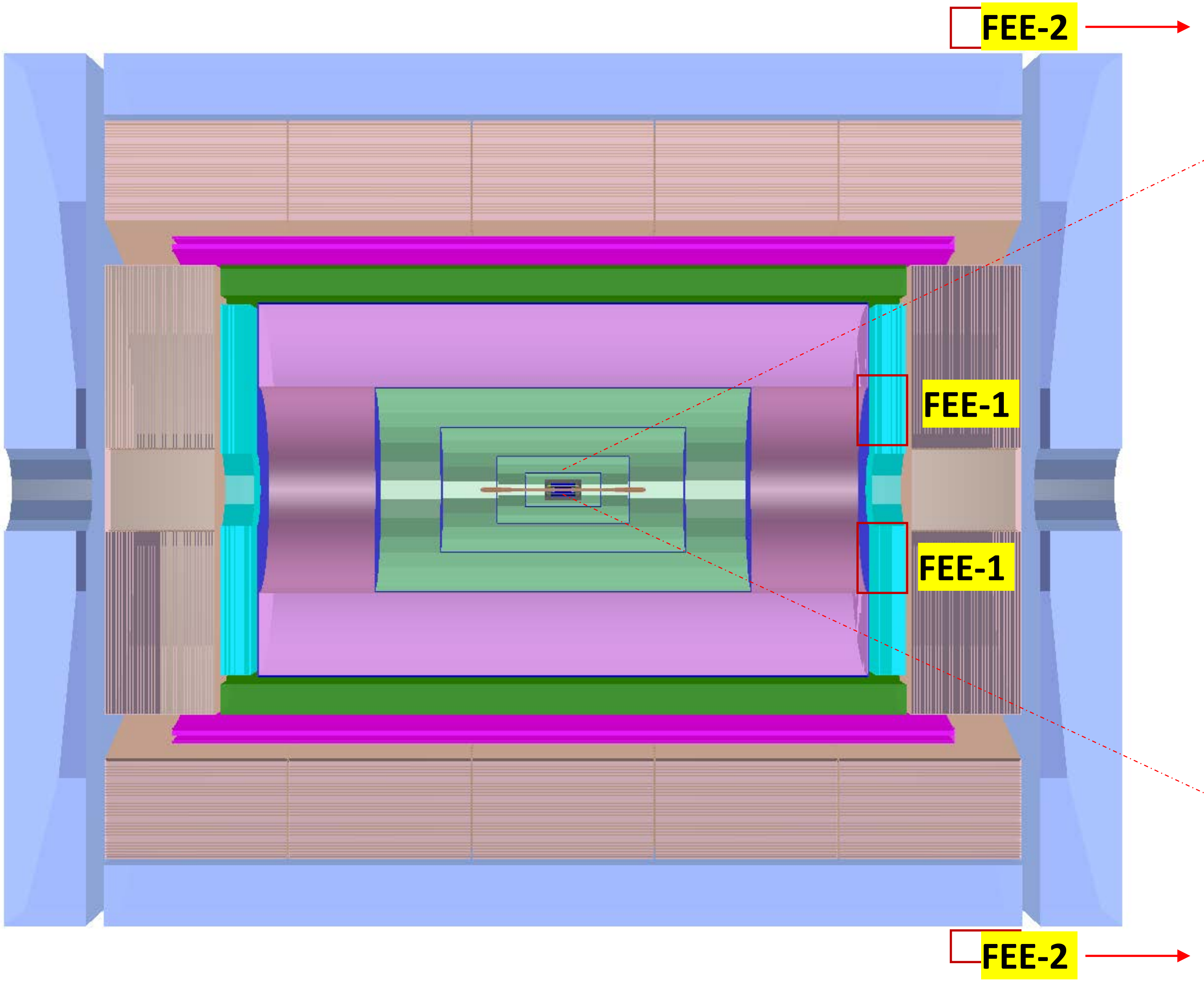
The structure is stable

Comparison of 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

Electronics scheme

Global design for DC Elec-TDAQ system

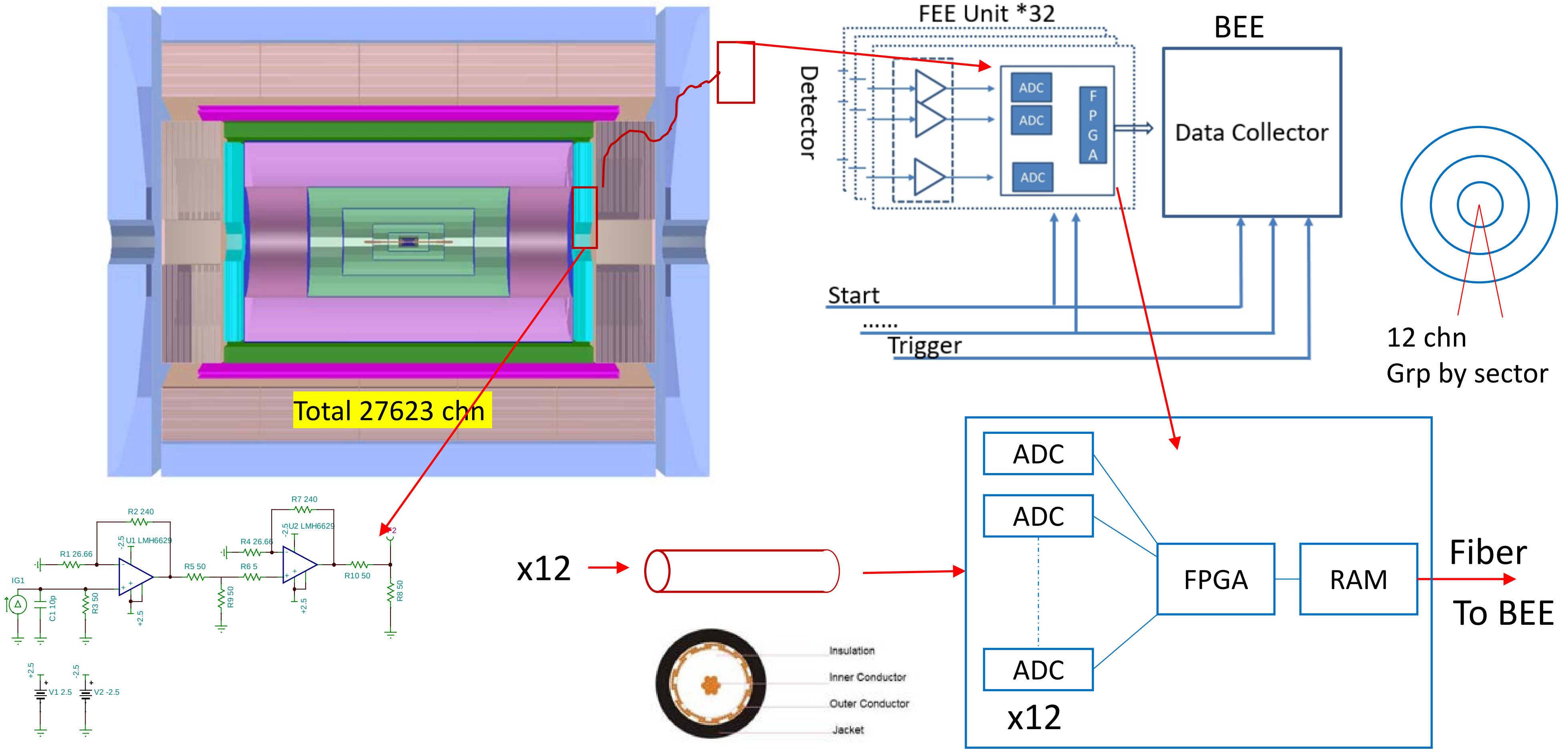


Considering : radiation hardness
Power consumption,
Material budget

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

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

Preliminary readout scheme of Drift Chamber



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

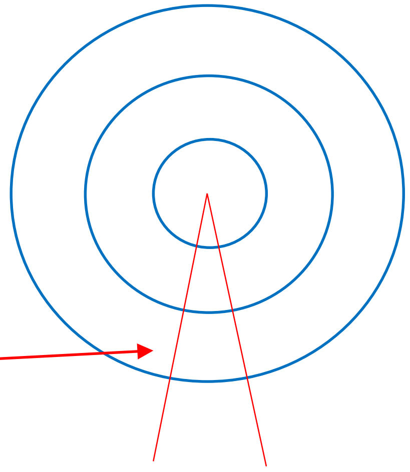
1.4kW for each end plate, air cooling is OK
no additional material bufget

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

ADC @1.3Gsps, 12bit

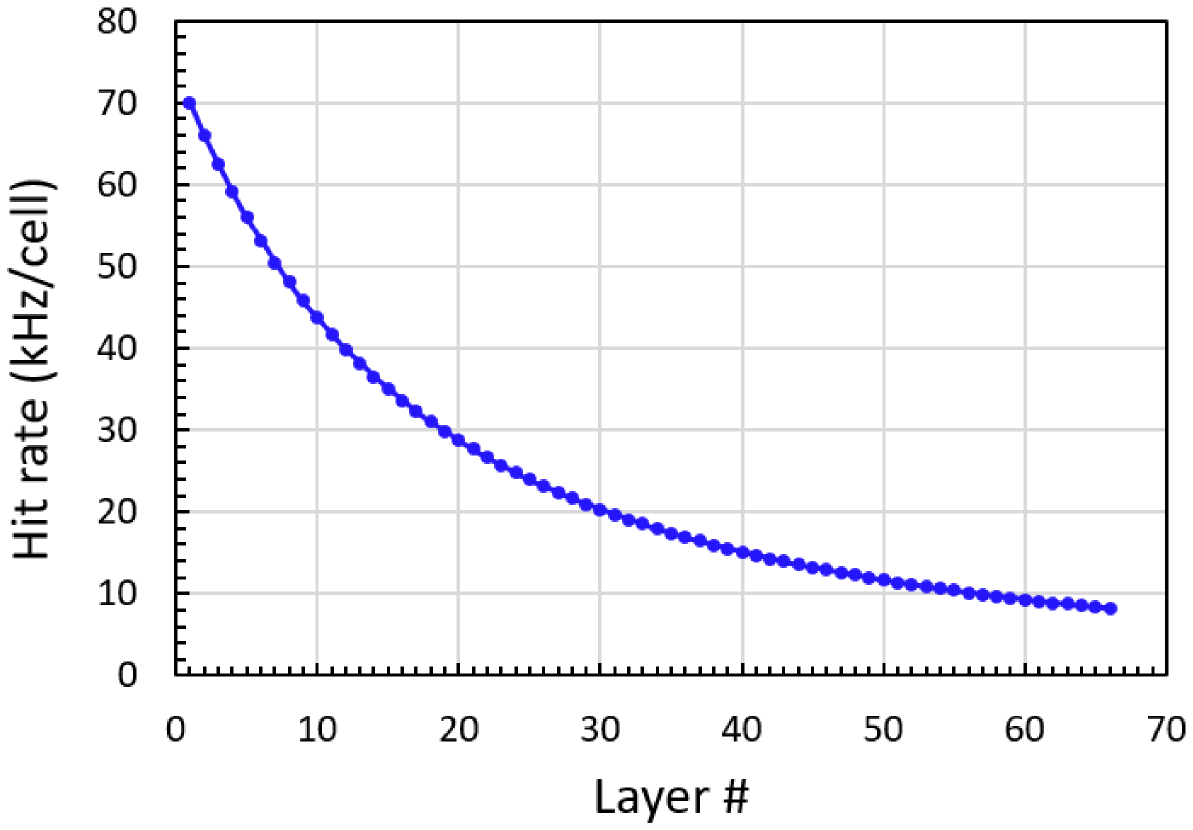
Data size estimation

- ADC sampling rate : 1.3Gsps, 12bit, sampling window: 1.5 μ s, 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



Hit rate and Occupancy at Z mode

- Lum. :1920* $10^{33}cm^{-1}s^{-1}$,
- Cross section: 31bn for Hadron
- Event rate : 60kHz (Hadron) +60 kHz (others)
- Hit rate: 120kHz *25 tracks*5 (background) =15MHz
- Hit rate for first layer: 70.4 kHz/cell
- Occupancy for first layer: 10.6%



Updated design parameters

R extension	600-1800mm
Length of outermost wires （cosθ=0.85）	5800mm
Thickness of inner CF cylinder： (for gas tightness, no load)	200μm (0.08% X_0)
Thickness of outer CF cylinder： (for gas tightness, no load)	300μm (0.13% X_0)
Outer CF frame structure：	Equivalent CF thickness: 1.8 mm (0.77% X_0)
Thickness of end Al plate:	20mm / 25mm (22.5X_0 / 28% X_0)
Cell size:	~ 18 mm × 18 mm
Cell number	27623
Diameter of field wire (Al coated with Au)	60μm
Diameter of sense wire (W coated with Au)	20μm
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC_4H_{10}=90:10
Gas + wire material	0.16% X_0

Performance

	Higgs	Z-pole
B-field (T)	3	2
Performance		
material budget barrel (X0)	1.14%	1.14%
material budget endcap (X0)	28% (plate) +1.8% (cables)	28% (plate) +1.8% (cables)
Npoints per full track	66	66
point resolution in rϕ (μm)	100	100
point resolution in rz (μm)	2000	2000
momentum resolution normalized: $\sigma(1/pT) = a \pm b/pT$	$2.1\times10^{-5} \pm 0.77\times10^{-3}/pT$	$3.2\times10^{-5} \pm 1.16\times10^{-3}/pT$
a (1/GeV)	2.1×10^{-5}	3.2×10^{-5}
b	0.77×10^{-3}	1.16×10^{-3}
K/π separation power @ 20GeV	3.2 σ	3.2 σ
dN/dx resolution	2.5%-2.6%	2.5%-2.6%
Hit rate (maximum)		70.4 kHz/cell
Occupancy (maximum)		10.6%
Readiness		
mechanical design	design reasonable, structure stable by FEA	
electronics	Readout scheme reasonable(discussed with electronics group)	
power consumption	FEE: 100mW/ch, 1.4 kW/end plate	
cooling	Air cooling	

Estimation of Cost

1.1		Chamber	10^4CNY	unit	3130.00
	1.1.1	End plate	405	2	810.00
	1.1.2	Outer frame structure	500.00	1	500.00
	1.1.3	Inner and outer cylinders	150.00	1	150.00
	1.1.4	Wire	710.00	+20% spare	710.00
	1.1.5	Feedthrough	530.00	+20% spare	530.00
	1.1.6	Wire test system	50	1	80
	1.1.7	Wiring tooling	300	1	350
1.2		Electronics			5170.00
	1.2.1	Readout Channel	0.17	27623*1.1 (10% backup)	5170.00
1.3		HV and Gas system			340.00
	1.3.1	High Voltage system	220.00	6HV crates, 50modules	220.00
	1.3.2	Gas system	120.00	1	120.00
total					8640

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. Next testbeam is planned
  - 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)