TPC at CEPC and how to address its limitations and feasibility

<u>Huirong Qi</u>

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Institute of High Energy Physics, CAS
Tsinghua University
Mini-Workshop: Experiment/Detector - Tracking and Calorimetery at Colliders, Jan.,18, 2019

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Preliminary R&D and open question

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Outline

- Baseline design
- Requirements and challenges
- Feasibility study of TPC detector
- R&D activities
- Summary

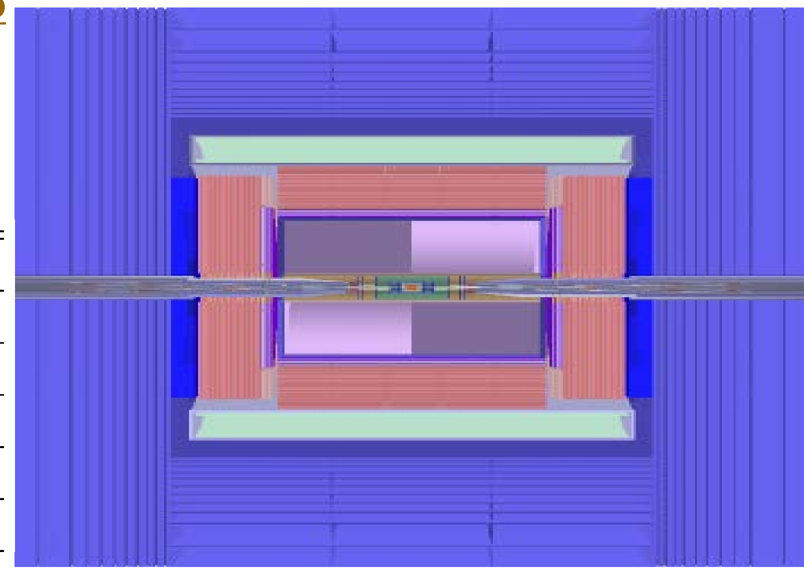
Three Detector Concepts (CEPC CDR)

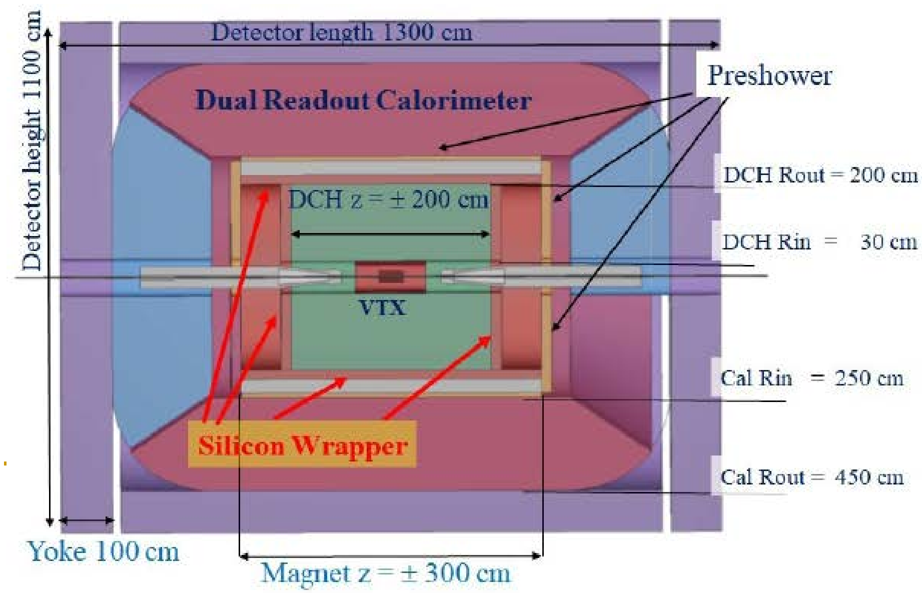
ArXiv:1811.10545

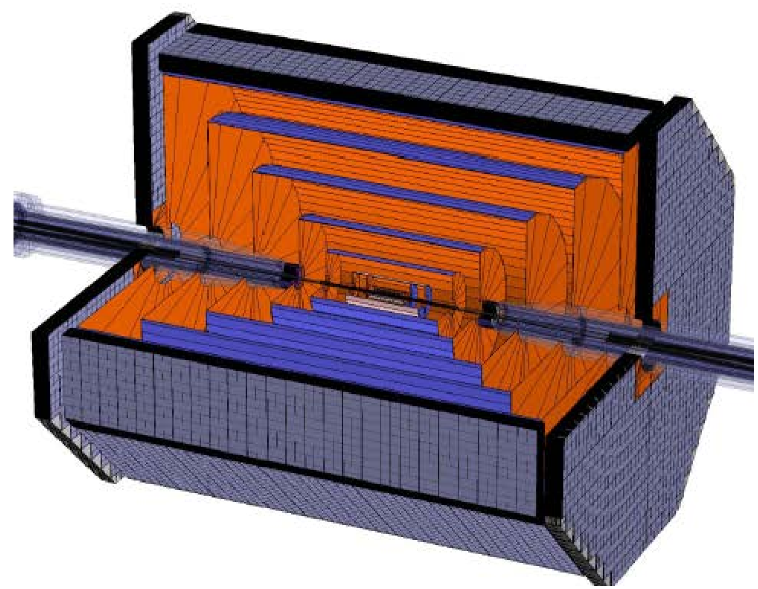
- Baseline: Silicon + TPC
- FST: all-silicon tracker
- IDEA: Silicon+Drift chamber (DCH)

Operation mode	$\sqrt{s}$ (GeV)	L per IP ($10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)
H	240	3
Z	91.2	32 (*)
W^+W^-	158–172	10

	Higgs	W	Z (3T)	Z (2T)
Number of IPs			2	
Beam energy (GeV)	120	80	45.5	
Circumference (km)			100	
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)			16.5 × 2	





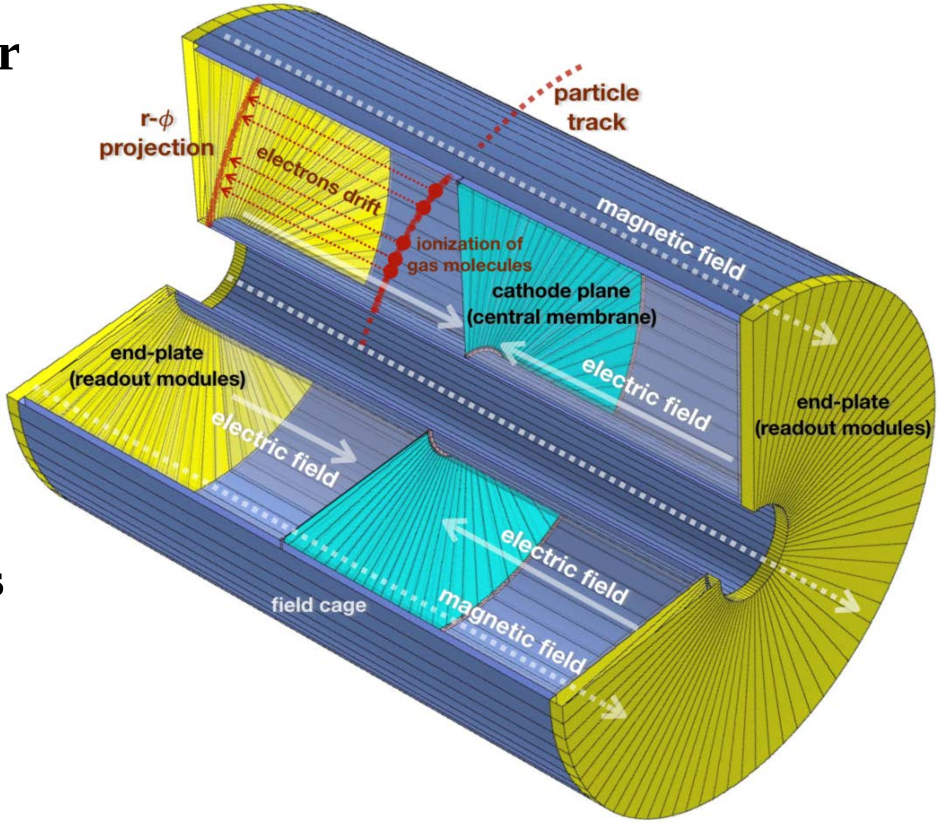


TPC detector at CEPC

TPC could directly provides three-dimensional space points; the gaseous detector volume gives a low material budget; and the high density of such space points enables excellent pattern recognition capability.

Why use TPC detector as the tracker detector?

- **Motivated by the H tagging and Z**
- **TPC is the perfect detector for HI collisions …(ALICE TPC…)**
- **Almost the whole volume is active**
- **Minimal radiation length (field cage, gas)**
- **Easy pattern recognition (continuous tracks)**
- **PID information from ionization measurements (dE/dx)**
- **Operating under high magnetic field**
- **MPGD as the readout**

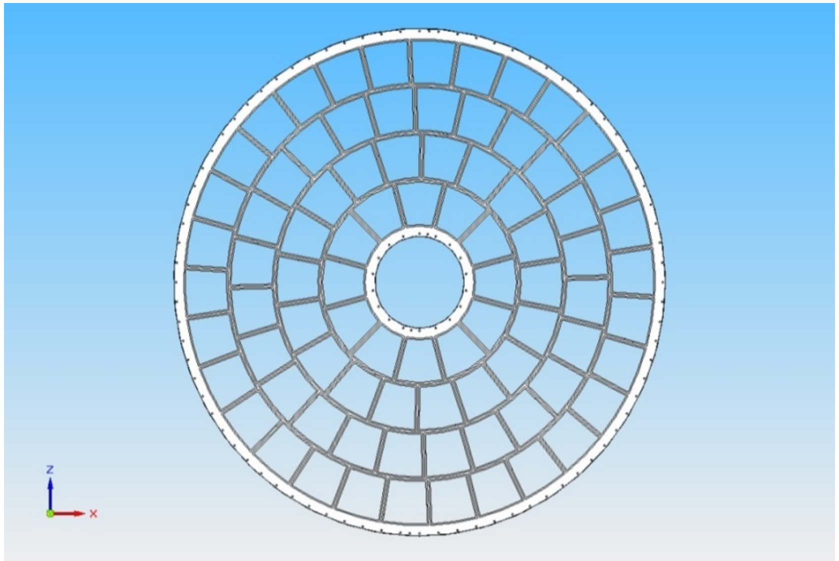


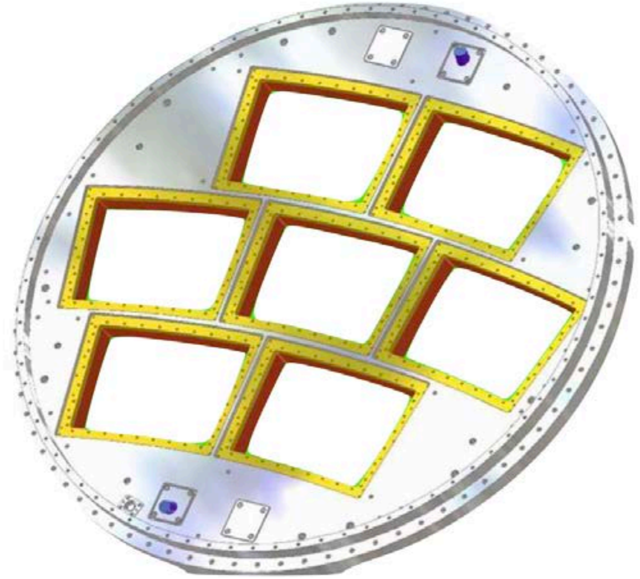
Overview of TPC detector concept

TPC requirements for CEPC

TPC detector concept:

- Under 3 Tesla magnetic field (Momentum resolution: ~10^{-4}/GeV/c with TPC standalone)
- Large number of 3D space points(~220 along the diameter)
- dE/dx resolution: <5%
- ~100 μm position resolution in rφ
  - ~60μm for zero drift, <100μm overall
  - Systematics precision (<20μm internal)
- TPC material budget
  - <1X_0 including outer field cage
- Tracker efficiency: >97% for pT>1GeV
- 2-hit resolution in rφ : ~2mm
- Module design: ~200mm×170mm
- Minimizes dead space between the modules: 1-2mm



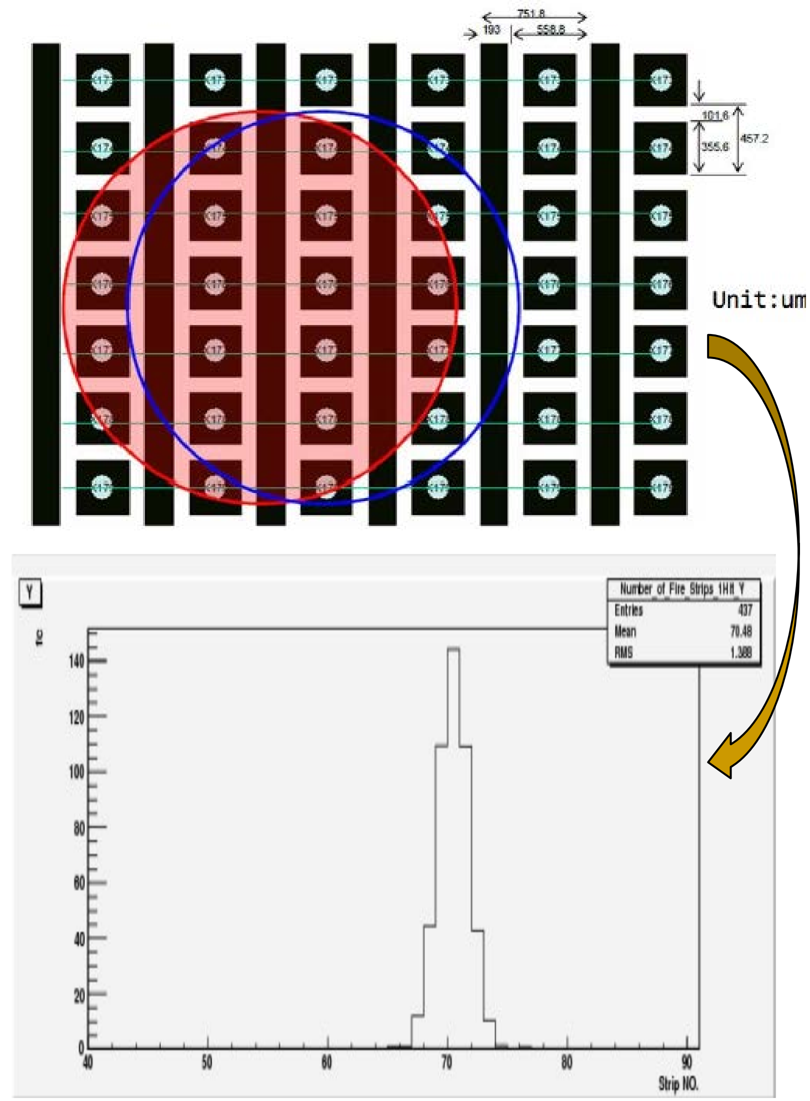


TPC detector endplate concept

Gas amplification detector module and pad size

Micro pattern detector:

- **GEM and Micromegas detector**
- **Electron cluster using Center-of-Gravity**
  - **Pitch: ~1mm**
  - **Pad Size: ~1mm×6mm**
- **High gain (5000-10000)**
- **High rate capability: MPGDs provide a rate capability over 10^5 Hz/mm^2 without discharges that can damage electronics.**
- **Intrinsic ion backflow suppression: Most of the ions produced in the amplification region will be neutralized on the mesh or GEM foil and do not go back to the drift volume.**
- **A direct electron signal, which gives good time resolution (< 100 ps) and spatial resolution (100 μm).**



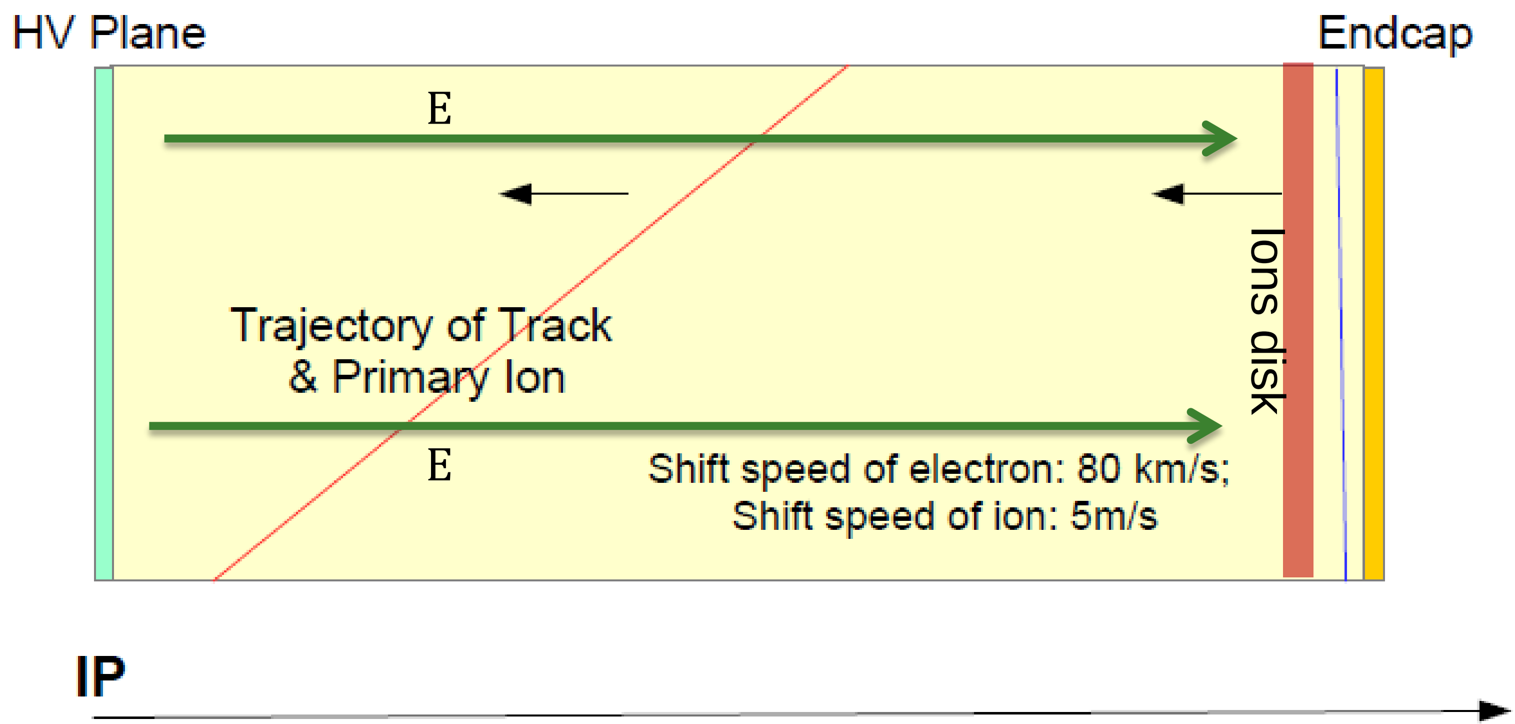
The profile of an electron cluster in GEMs detector

- TPC possible limitations
    - Ions back flow in chamber
    - Calibration and alignment
    - Low power consumption FEE ASIC chip

Feasibility study of TPC

- Would it be Limited by
  - Voxel occupancy
  - Primary ions along the track in the chamber
  - Amplification ions create the ions disk back to the chamber (× Gain)
  - Charge Distortion induced by the ions: Mainly from Ion back flow

Voxel size defined (3D space bucket):
Pad size × $T_{sample} \cdot V_{drift}$



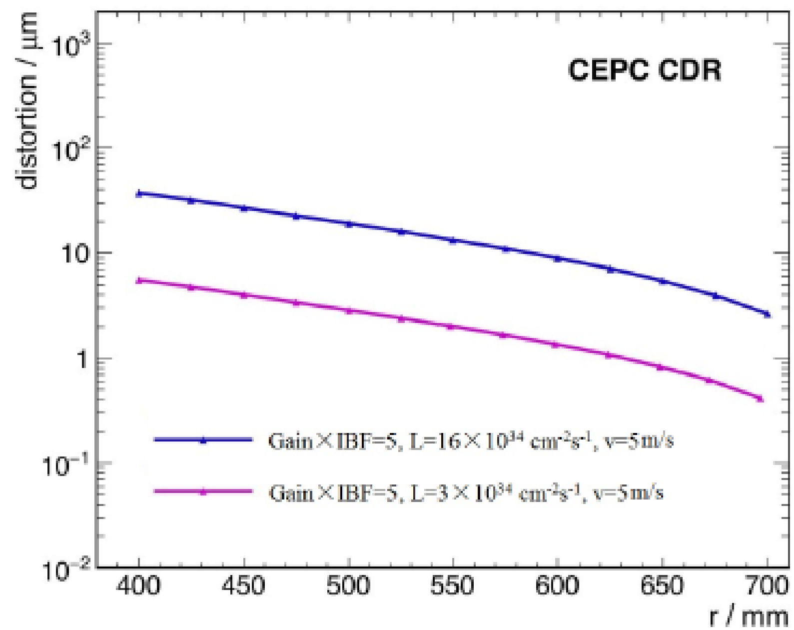
Total ions in chamber: ~ Back flow ions ~(1 + k), k = Gain × IBF + Primary

Feasibility study of TPC at Z pole

ArXiv: 1704.04401

- Occupancy simulation
  - Gain×IBF refers to the number of ions that will escape the end-plate readout modules per primary ionization, obtained by the multiplication of the readout modules gain and the ion backflow reducing rate (IBF)
- L : the luminosity in units of $10^{34}cm^{-2}s^{-1}$
- Voxel size: 1mm×6mm ×2mm @DAQ/40MHz
- Maximal occupancy at TPC inner most layer: ~10^{-5} (safe)
- Full simulation: 9 thousand Z to qq events
- Bhabha events: a few nb
- Background considered ? (Need careful designed Shielding/detector protection)

Pad size : 1mm×6mm
T_{sample} : 25ns
V_{drift} : 80μm/ns



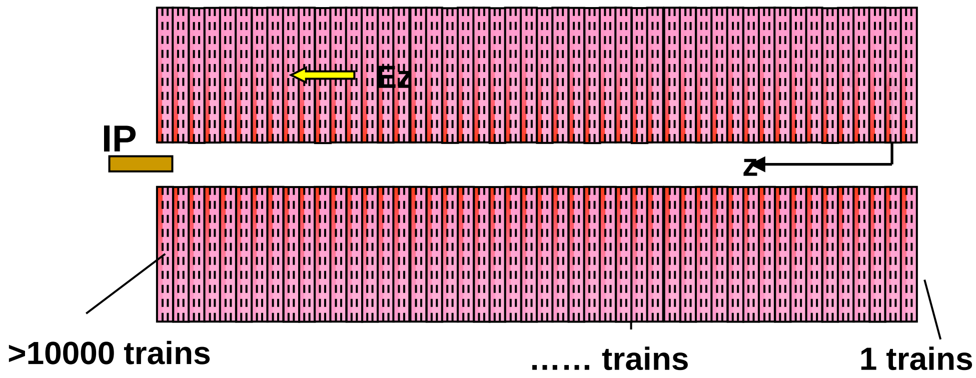
Distortion on the hit position reconstruction

To conclude, the TPC will be able to be used if the Gain×IBF can be controlled to a value smaller than 5.

Technical challenges of TPC for CEPC

Ion Back Flow and Distortion

- Goal:
  - Operate TPC at high luminosity at Z pole run
  - No Gating options
- IBF control similar with ALICE TPC upgrade
- ~100 μm position resolution in rφ
- Distortions by the primary ions at CEPC are negligible
- Manu ions discs co-exist and distorted the path of the seed electrons
- The ions cleaned during the ~us period continuously
- Continuous device for the ions
- Long working time



Amplification ions from the endplate @CEPC

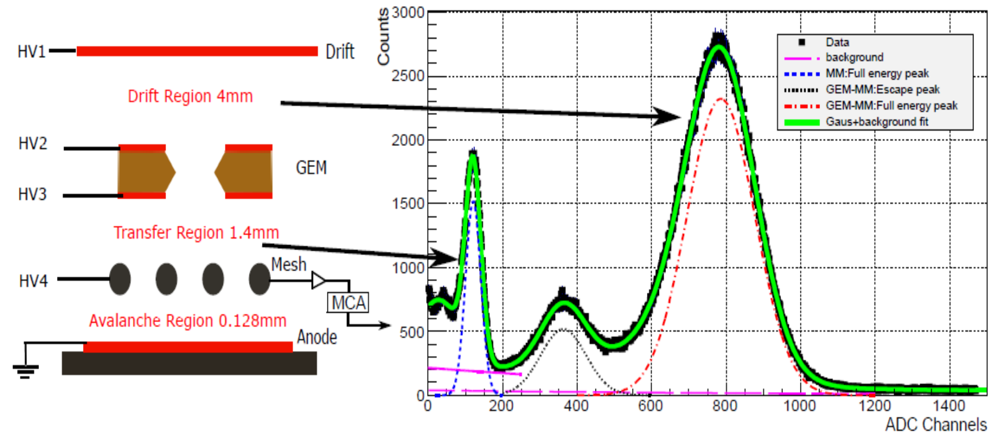
	ALICE TPC	CEPC TPC
Maximum readout rate	>50kHz@pp	w.o BG?
Gating to reduce ions	No Gating	No Gating
Continuous readout	No trigger	Trigger?
IBF control	Build-in	Build-in
IBF*Gain	<10	<5
Calibration system	Laser	NEED

Compare with ALICE TPC and CEPC TPC

Feasibility study of TPC detector

Continuous IBF module:

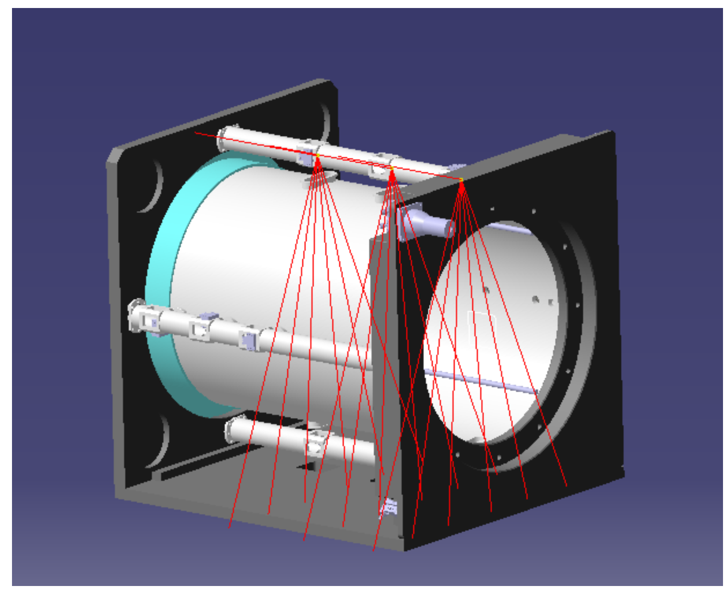
- Operation at Higgs and Z-pole run
- Continuous Ion Back Flow due to th continuous beam structure
- Low discharge and spark possibility
- Space charge effect for IBF
- Gain: 5000-6000
- Good energy resolution: <20%



Continuous IBF prototype and IBF × Gain

Laser calibration system:

- The ionization in the gas volume along the laser path occurs via two photon absorption by organic impurities (Nd:YAG laser @266nm)
- Laser calibration system around the chamber
- Calibration of the drift velocity, gain uniformity, the distortion
- High stability of the laser beam (<5μm)



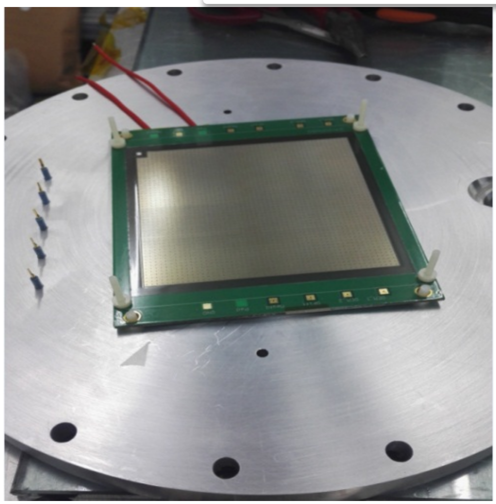
TPC prototype integrated with laser system

- Some R&D activities
  - TPC detector module -> IBF control
  - TPC detector prototype -> Calibration
  - Low power consumption -> FEE ASIC chip

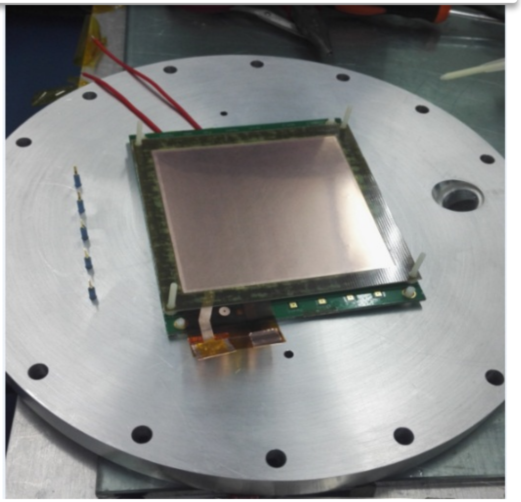
TPC detector module@ IHEP

DOI: 10.1088/1748-0221/12/04/P0401 JINST，2017.4
DOI: 10.1088/1674-1137/41/5/056003 , CPC,2016.11
DOI: 10.7498/aps.66.072901Acta Phys. Sin. 2017,7

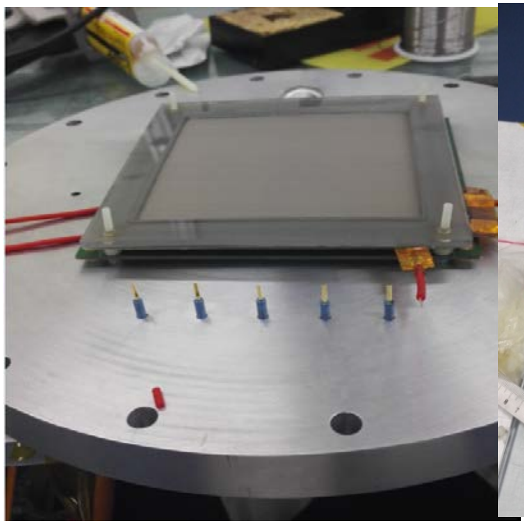
- Study with GEM-MM module
  - New assembled module
  - Active area: 100mm×100mm
  - X-tube ray and 55Fe source
  - Bulk-Micromegas assembled from Saclay
  - Standard GEM from CERN
  - Avalanche gap of MM:128μm
  - Transfer gap: 2mm
  - Drift length:2mm~200mm
  - pA current meter: Keithley 6517B
  - Current recording: Auto-record interface by LabView
  - Standard Mesh: 400LPI
  - High mesh: 508 LPI



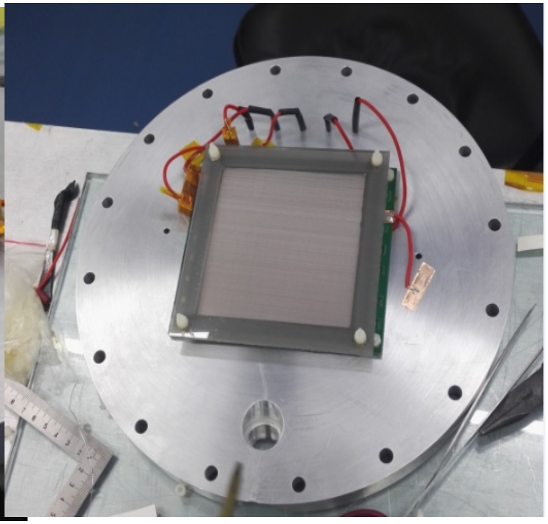
Micromegas(Saclay)



GEM(CERN)



Cathode with mesh

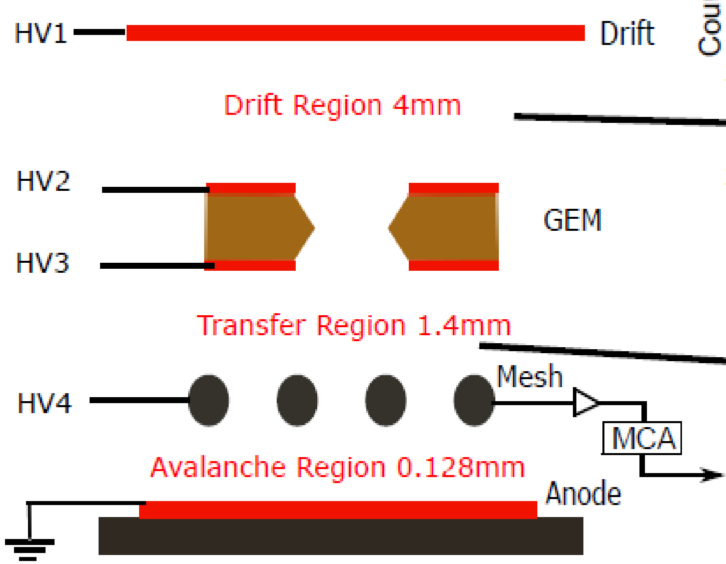


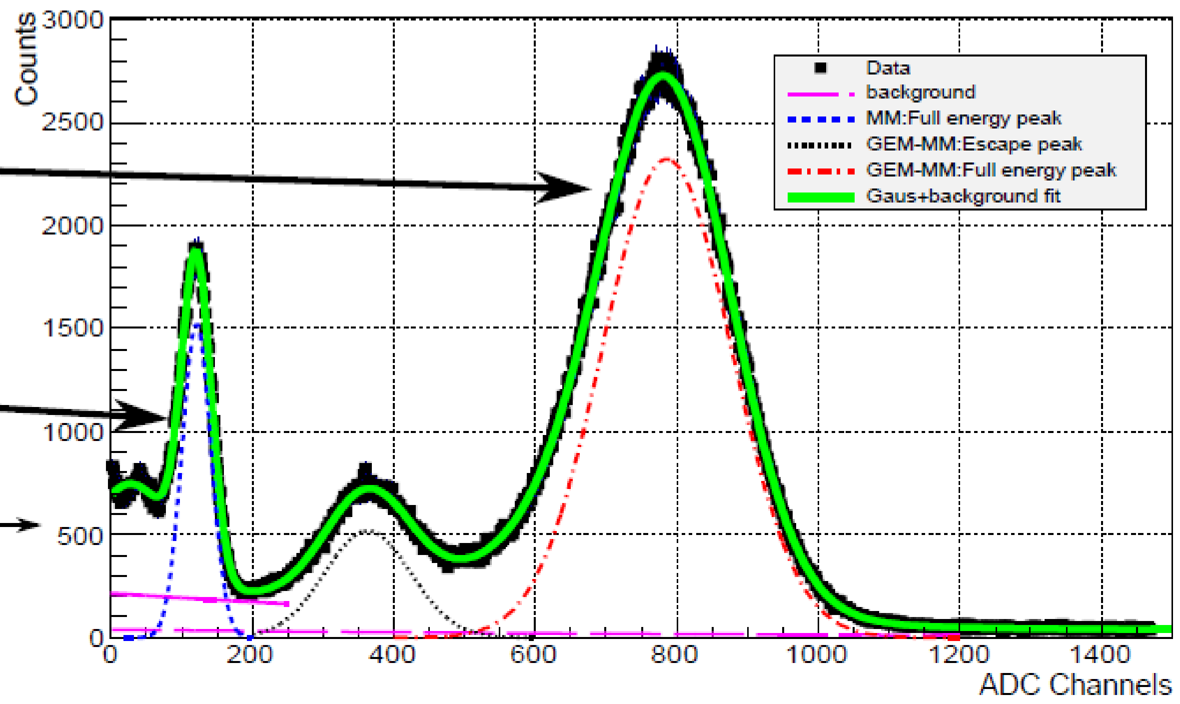
GEM-MM Detector

GEM+MM@CEPC R&D

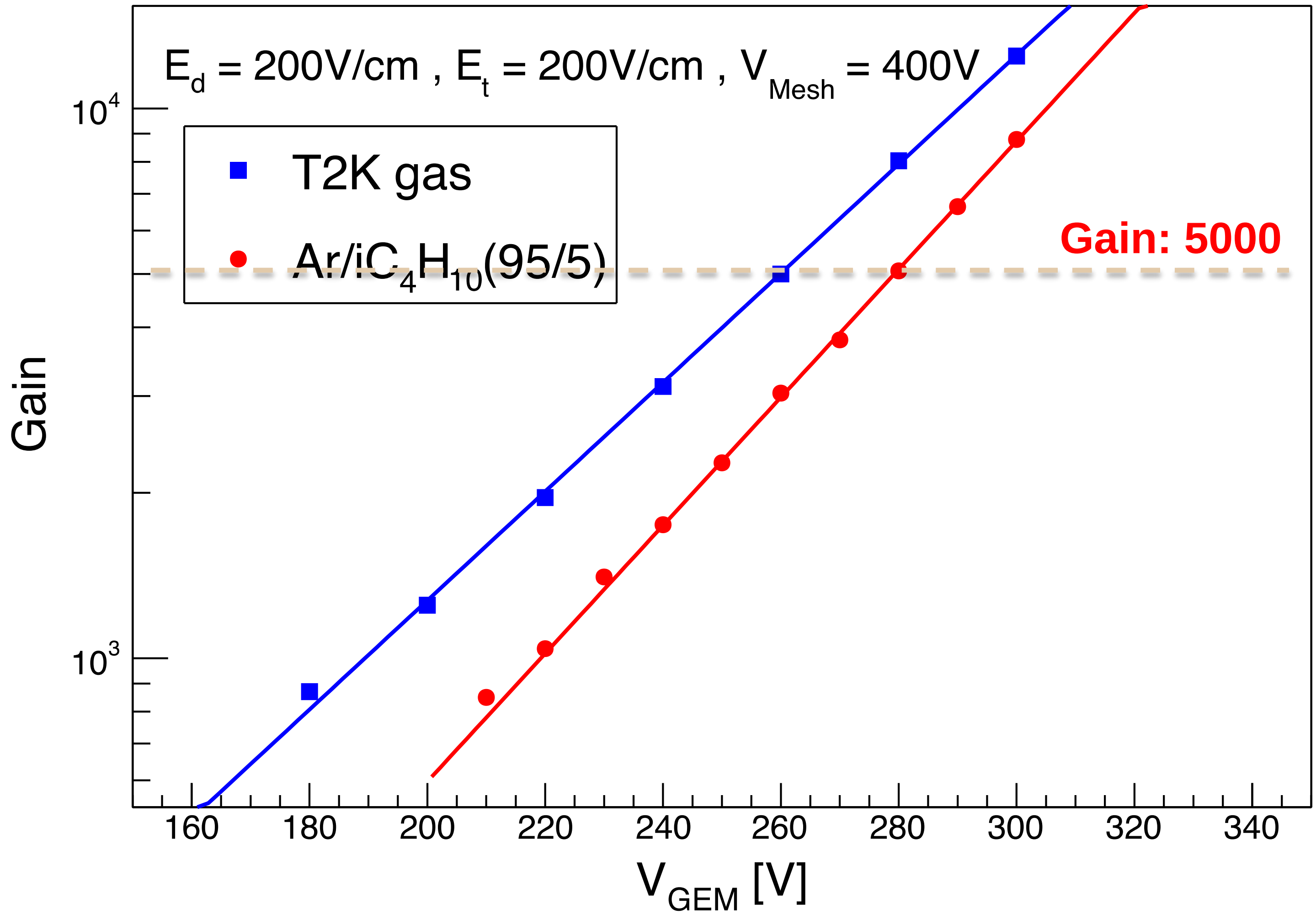
e+e- machine
Primary N_{eff} is small: ~30
Pad size:1mm×6mm

Photo peak and escape peak are clear!
Good electron transmission.
Good energy resolution.

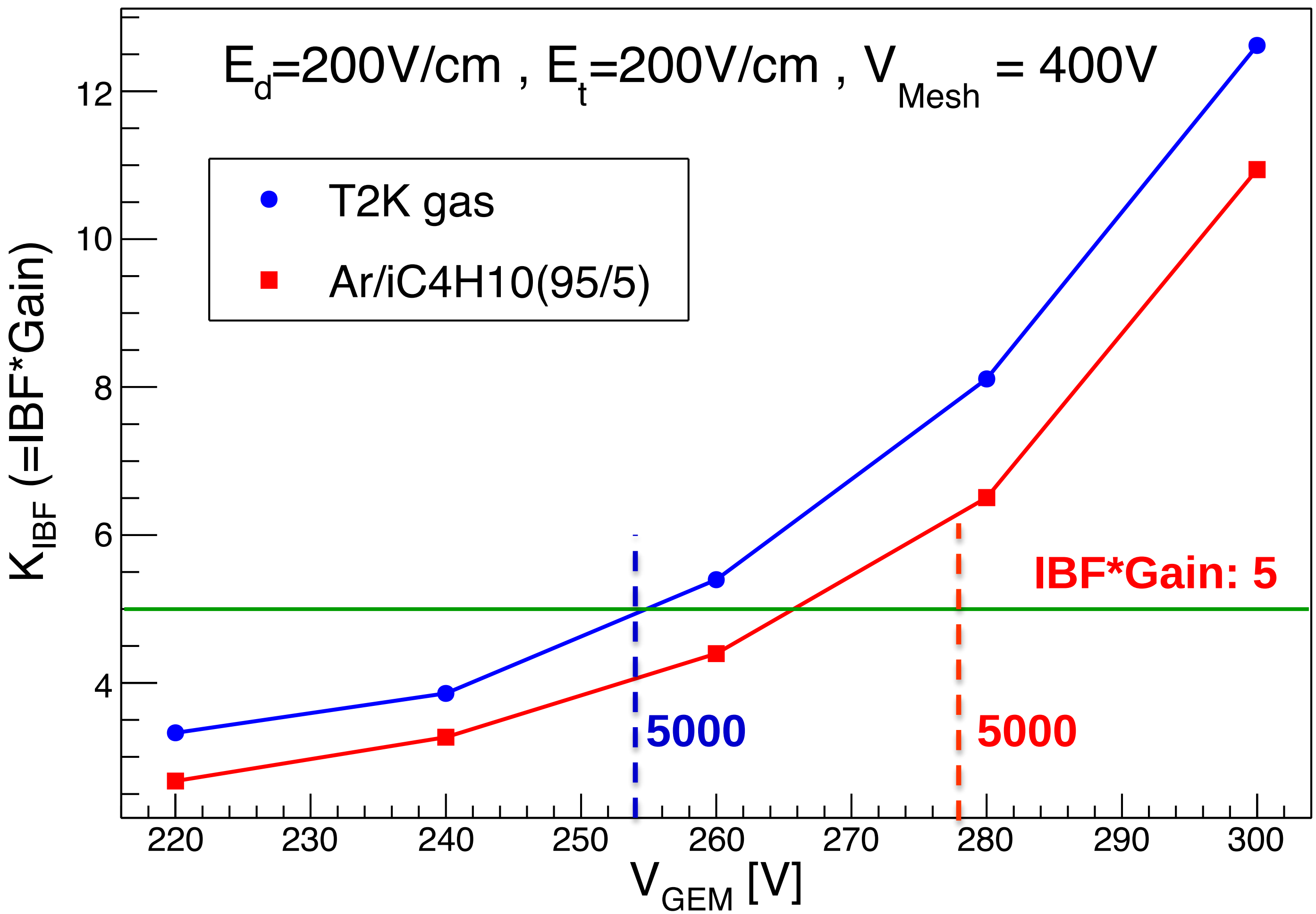




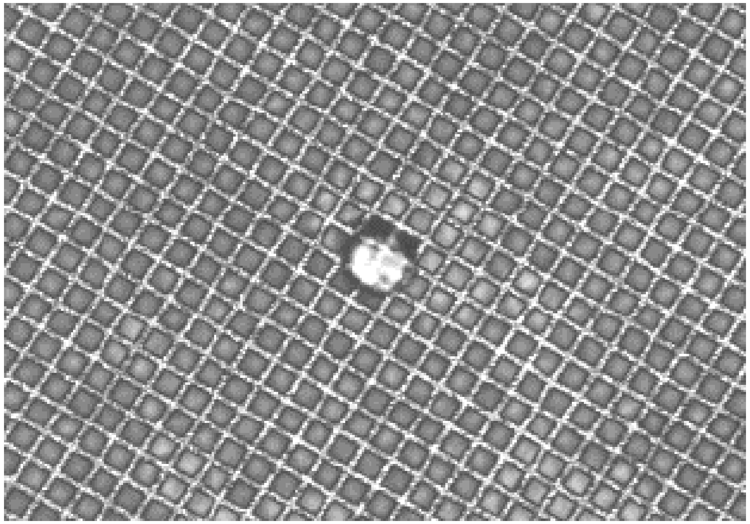
Gain of the hybrid structure detector

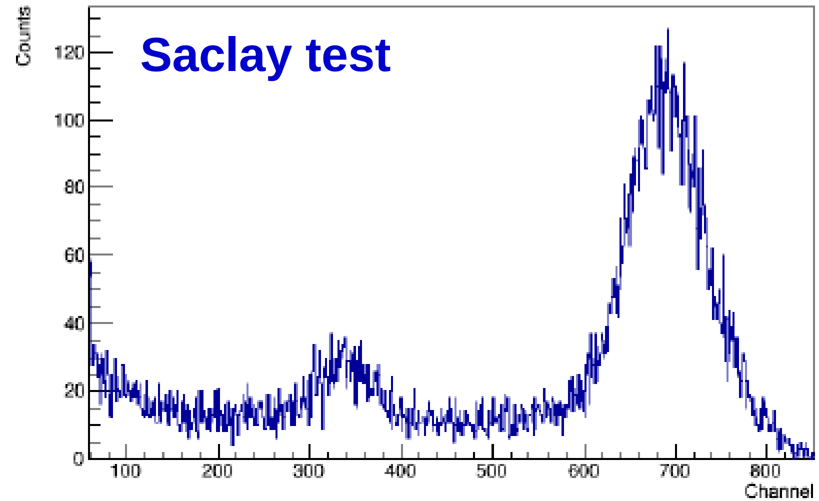


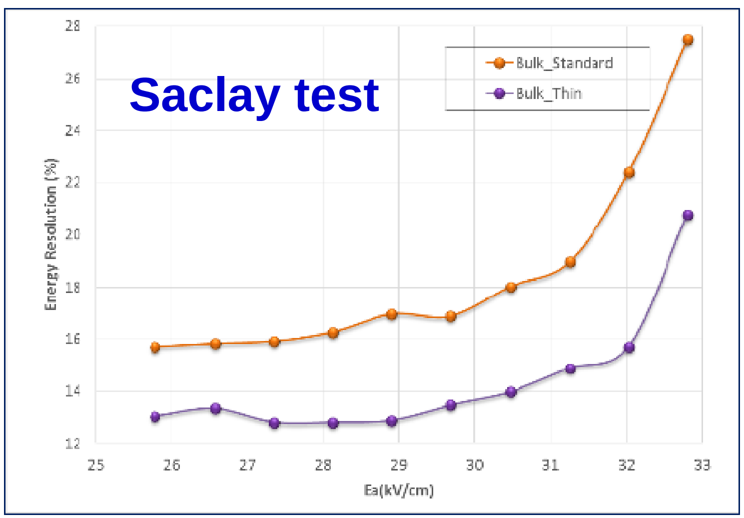
Key IBF factor: IBF×Gain

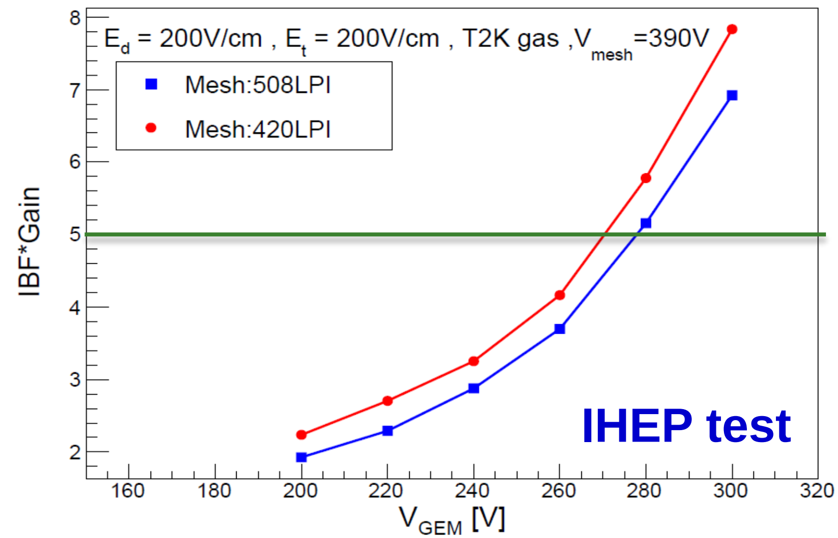


High mesh and lower IBF





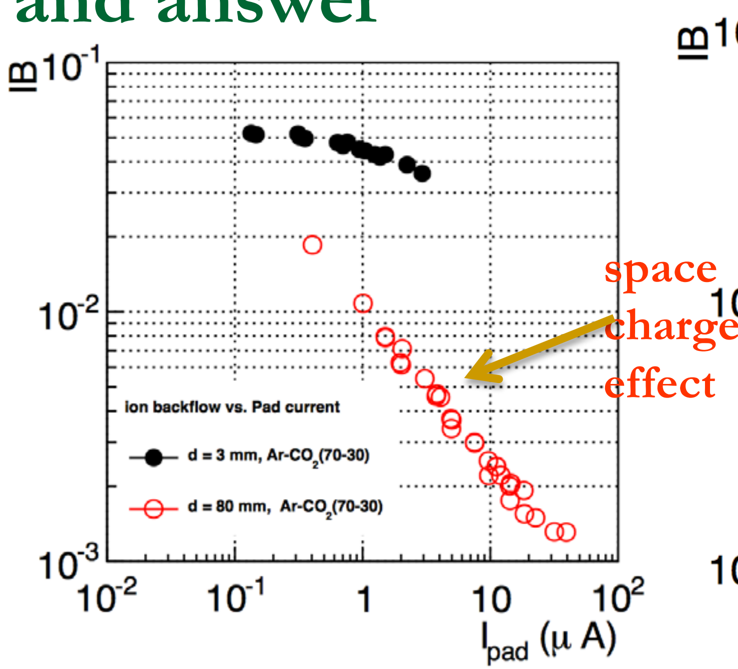


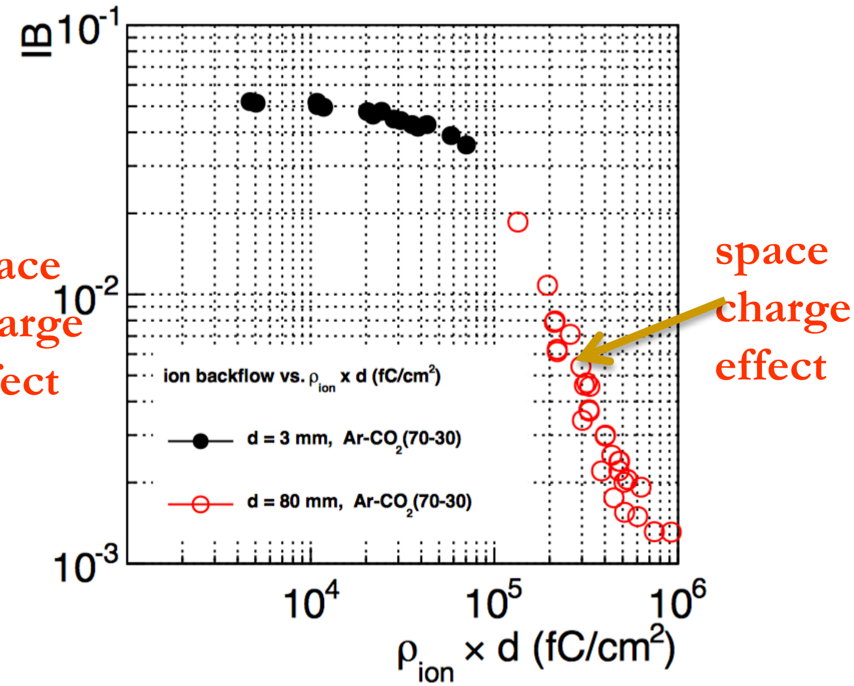


- From July, the high mesh of 508LPI has been assembled with CEA-Saclay collaboration. The preliminary results indicates that it could reach the lower IBF and better performance.

- Space charge to decrease IBF

Check and answer





http://iopscience.iop.org/article/10.1088/1748-0221/9/04/C04025/pdf

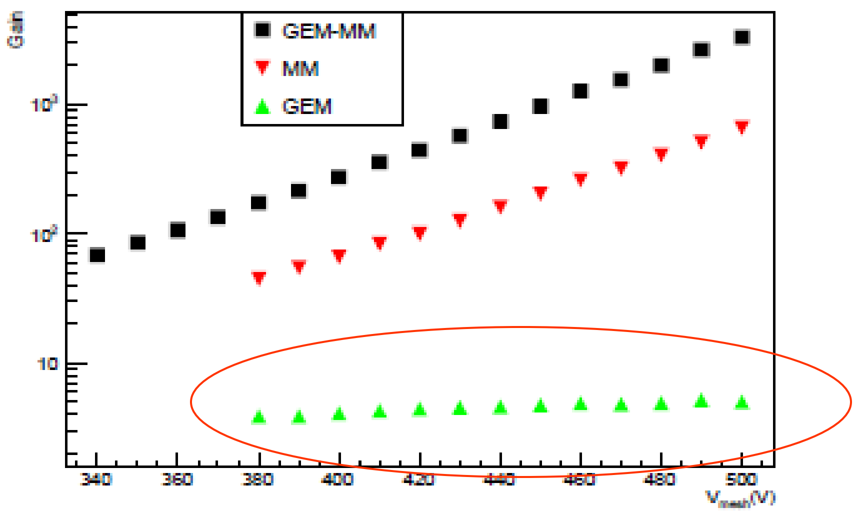
https://www.sciencedirect.com/science/article/pii/S0168900216308221

High rate and lots of ions make space charge effect to decrease IBF possibility !!!

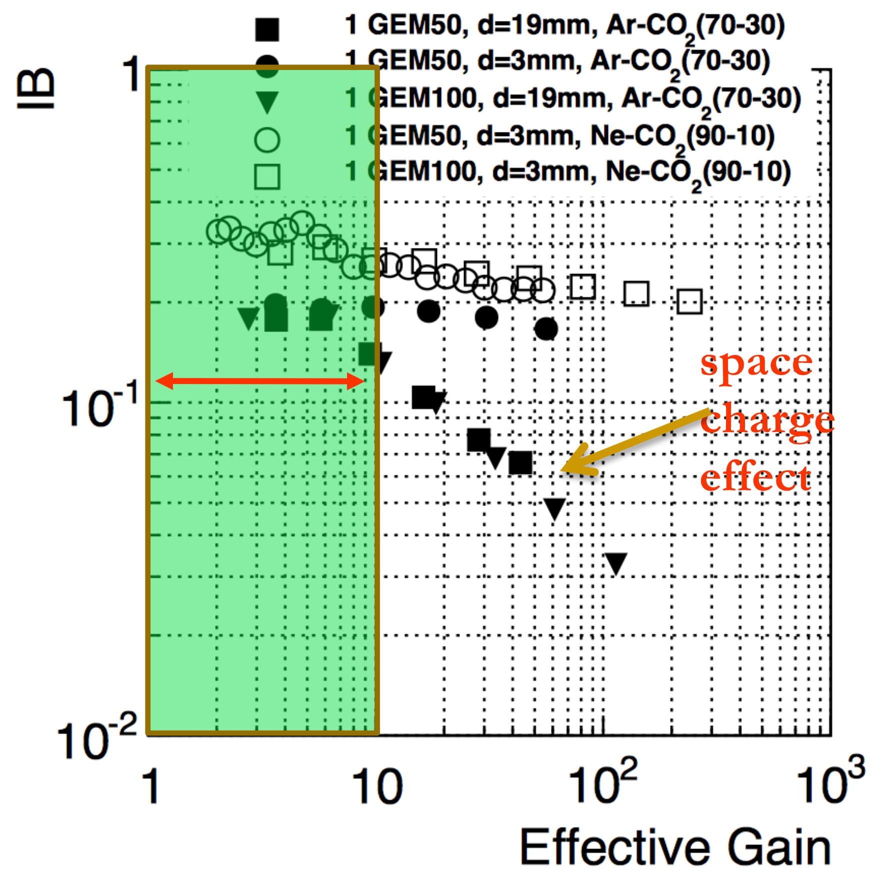
Check and answer -Gain

Single GEM with very low Gain in our Exp.

DOI: 1609.08010

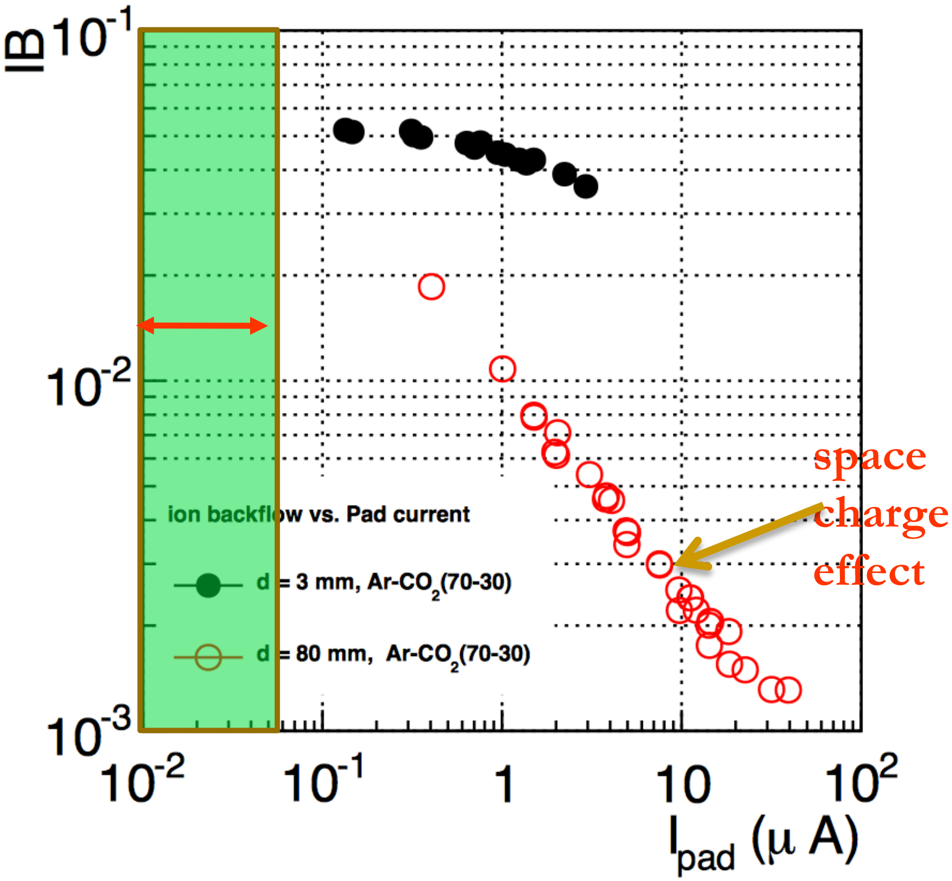


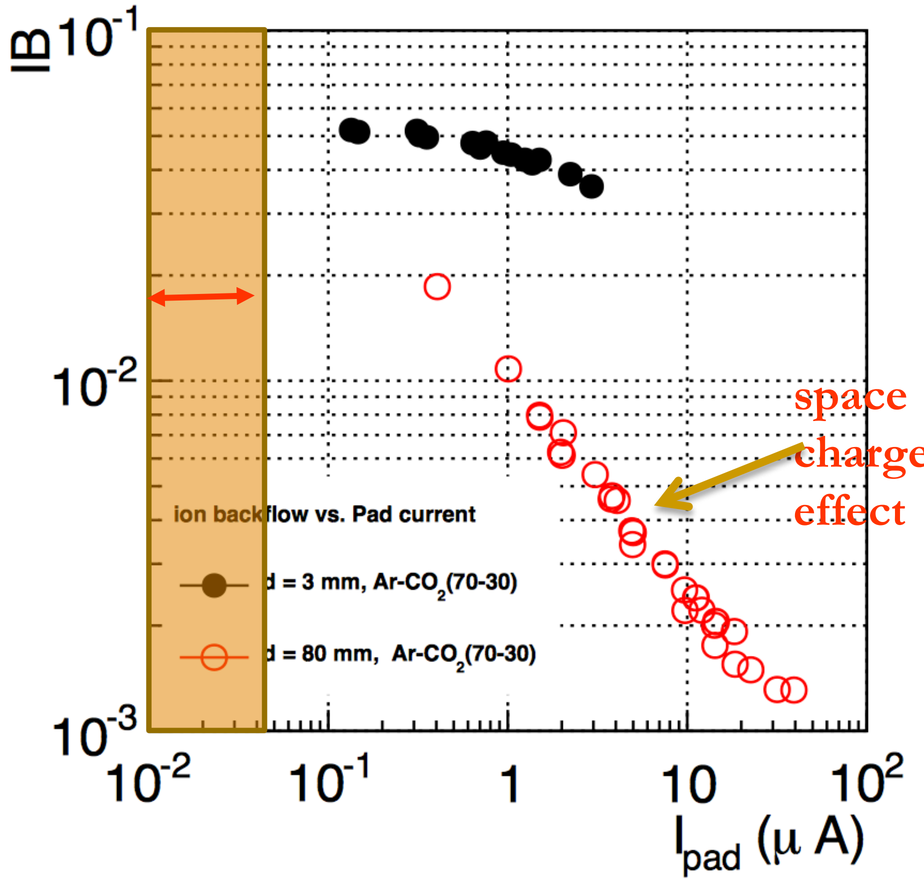
(b)



Check and answer- I_{pad}

Current of Pad is very low in our Exp.

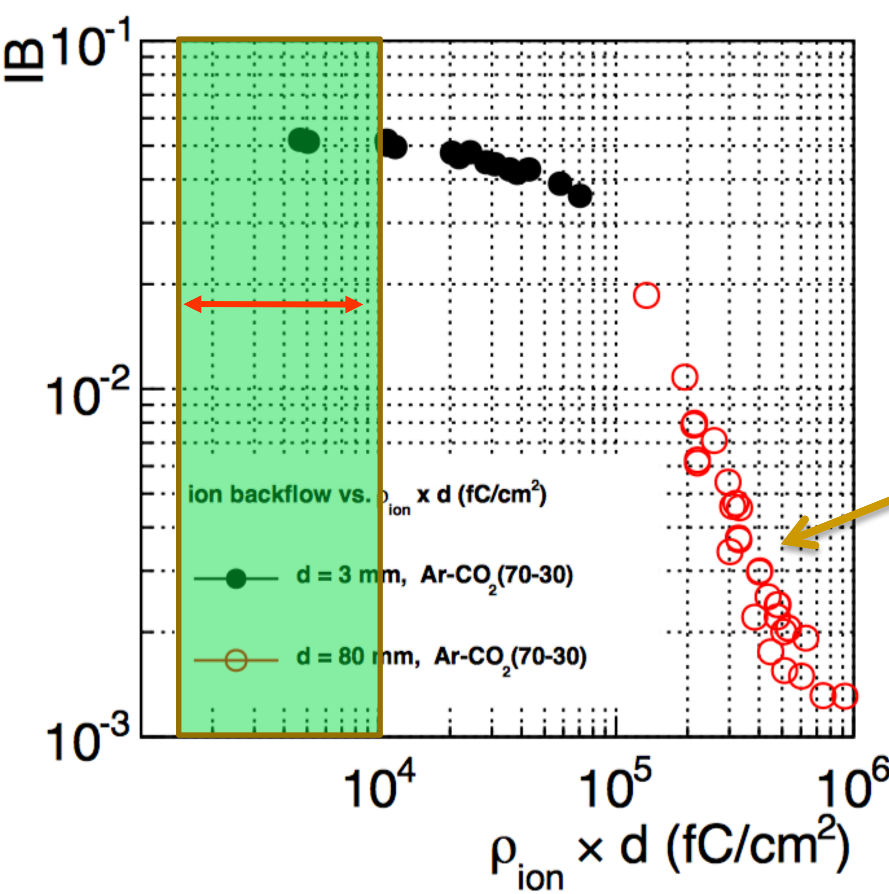




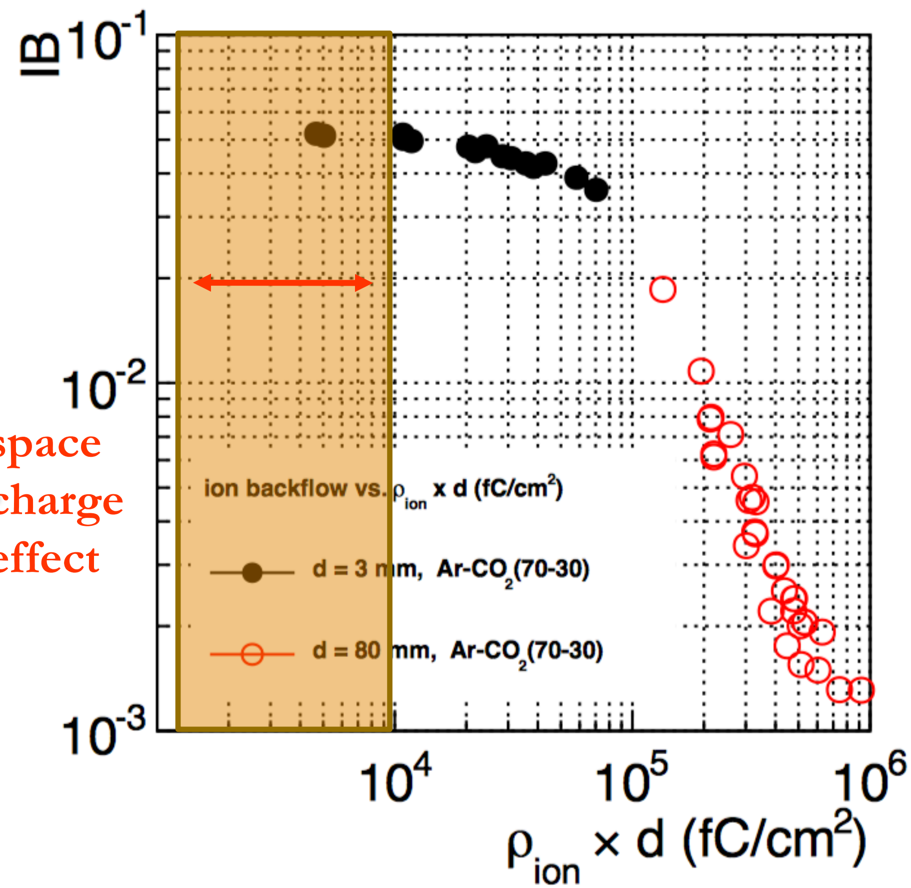
Green， T2K， Et=200V/cm, Ed=200V/cm, V_mesh=400V, V_Gem:30~300V
Yellow， Ar/iso(95/5) ， Et=200V/cm, Ed=200V/cm, V_mesh=400V, V_Gem:30~300V

Check and answer- $\rho_{ion} \times d$

Current of Pad is very low in our Exp.



space charge effect



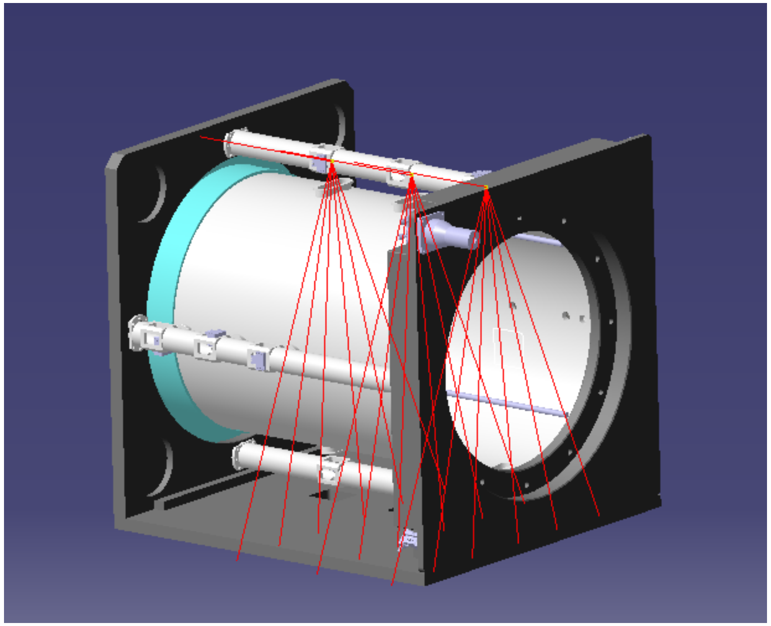
Green: T2K，Yellow: Ar/iso(95/5)

T2Kgas Ic: 4pA～59pA，～10^3 （fC/cm^2）
Ar/iso gas Ic : 3.5pA~53pA, ～10^3 （fC/cm^2）

Motivation of the TPC prototype

- Study and estimation of the distortion from the IBF and primary ions with the laser calibration system
- Main parameters
  - Drift length: ~510mm, Readout active area: 200mm×200mm
  - Integrated the laser calibration with 266nm
  - GEMs/Micromegas as the readout
  - Matched to assembled in the 1.0T PCMAG

1. TPC chamber
2. Laser calibration



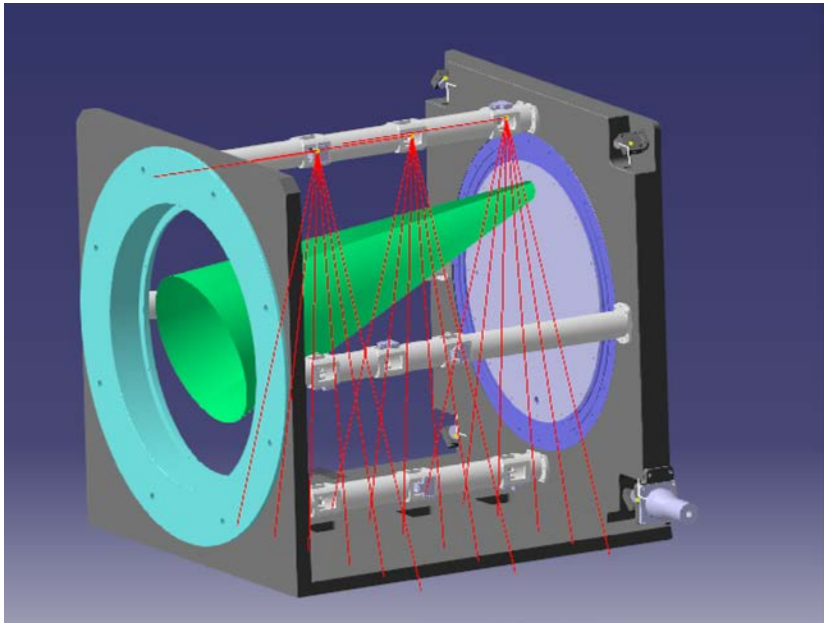
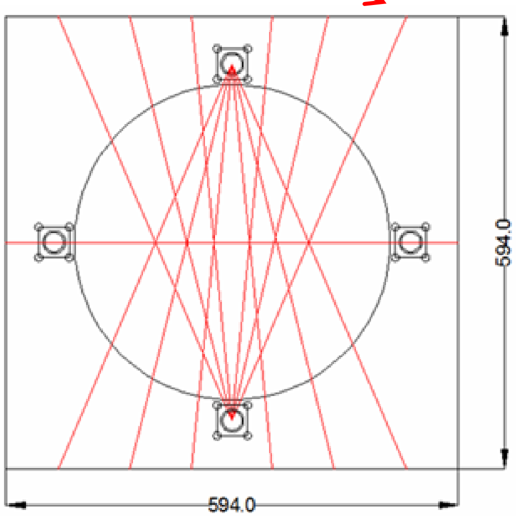


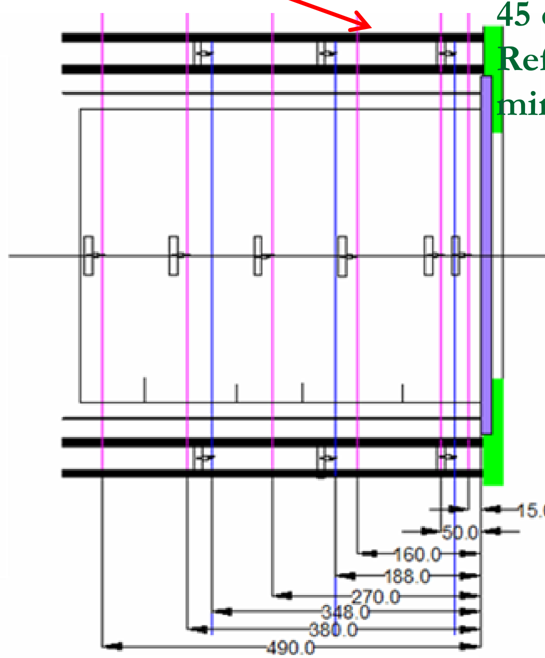
Diagram of the TPC prototype with the laser calibration system

Laser map in drift length

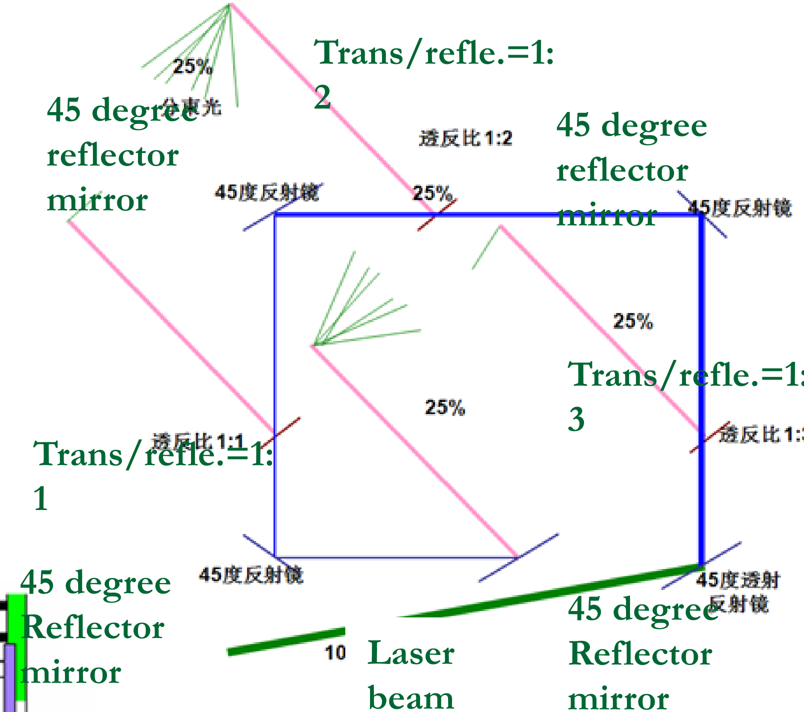
- Size: ~0.85mm×0.85mm
- Transmission and reflection mirrors
- Aluminum board integrated the laser device and supports
- Drift velocity in Z
- Uniformity in X-Y plane



Laser map in X-Y plane

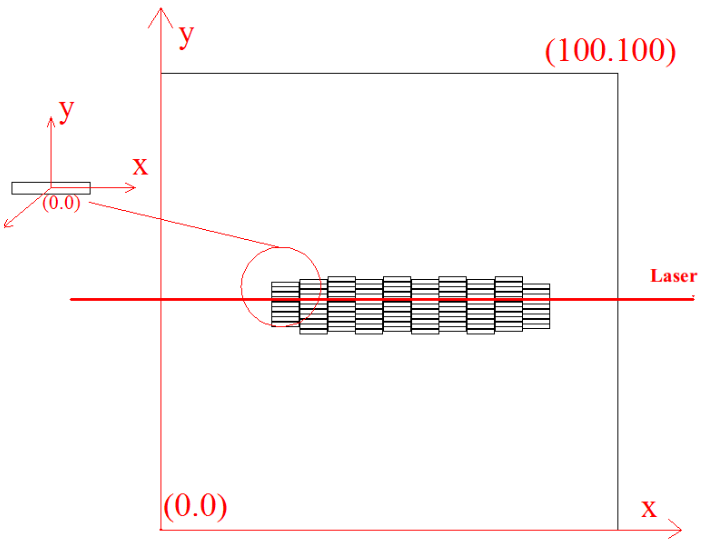


Laser map along Z

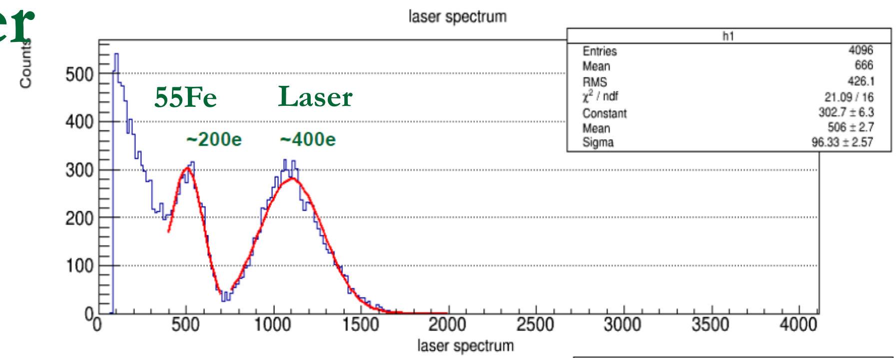


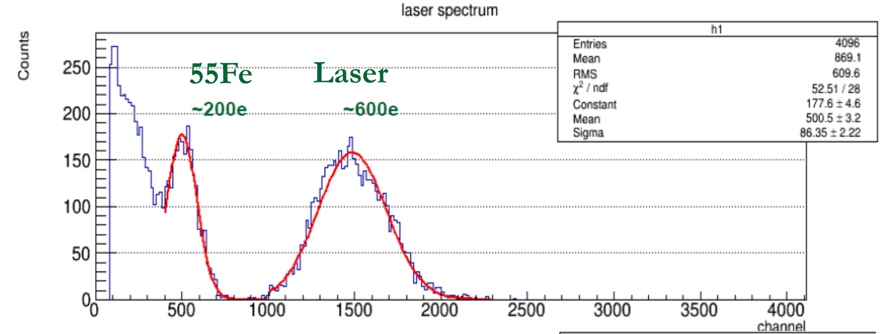
Detector with the laser system

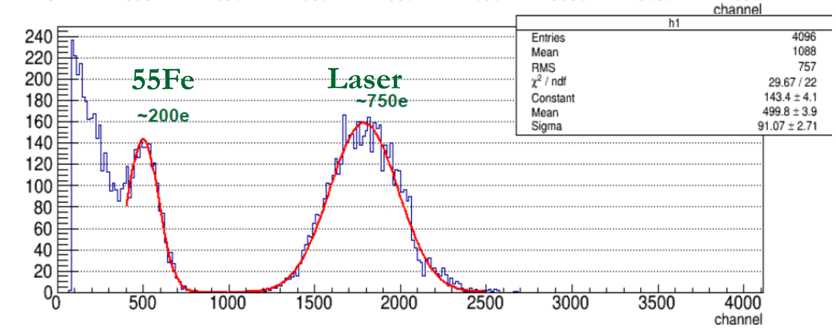
Preliminary test with the laser

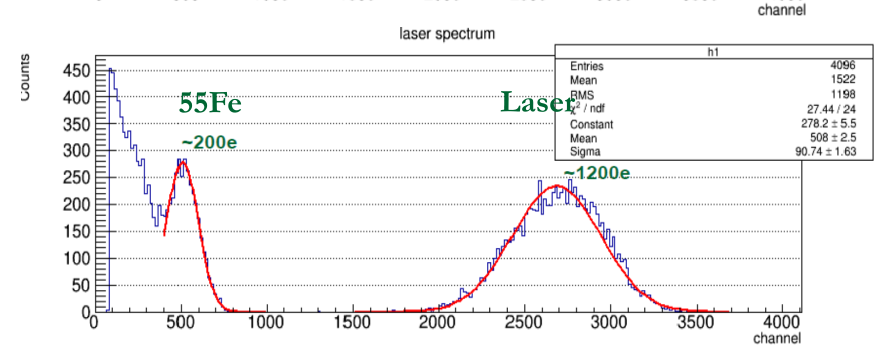


- Readout board, 128 Channels electronics, DAQ and laser mirror and PCB board have been done and assembled
- TPC barrel mount and re-mount with the Auxiliary brackets
- TPC preliminarily tested with 55Fe and the different power laser beam
- Optimization of the laser studied

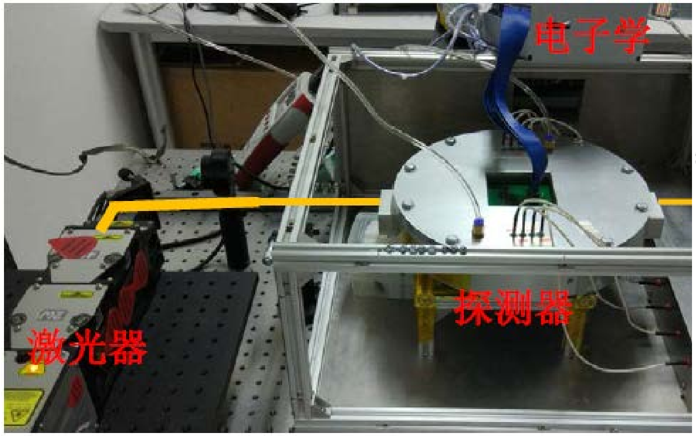


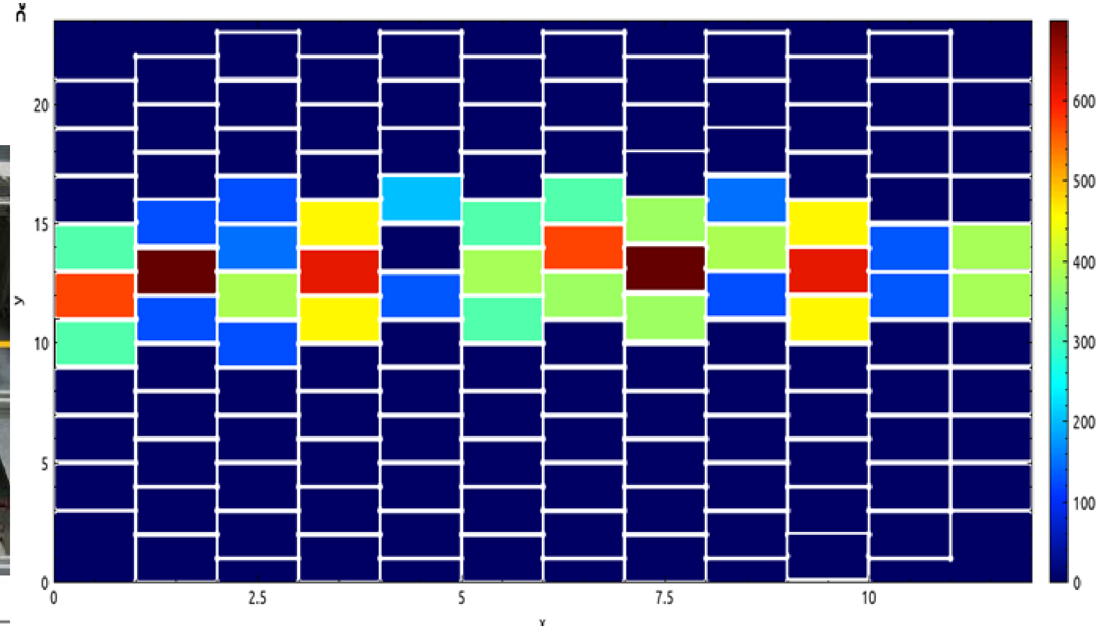


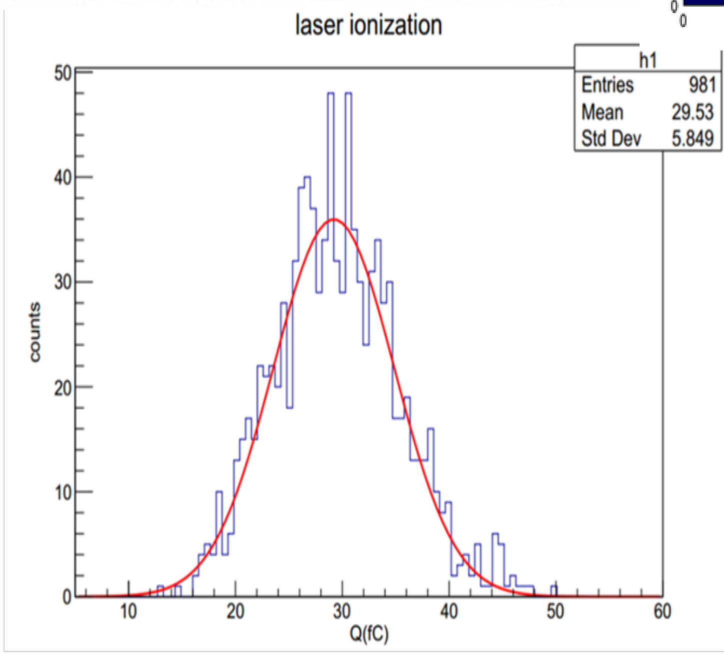


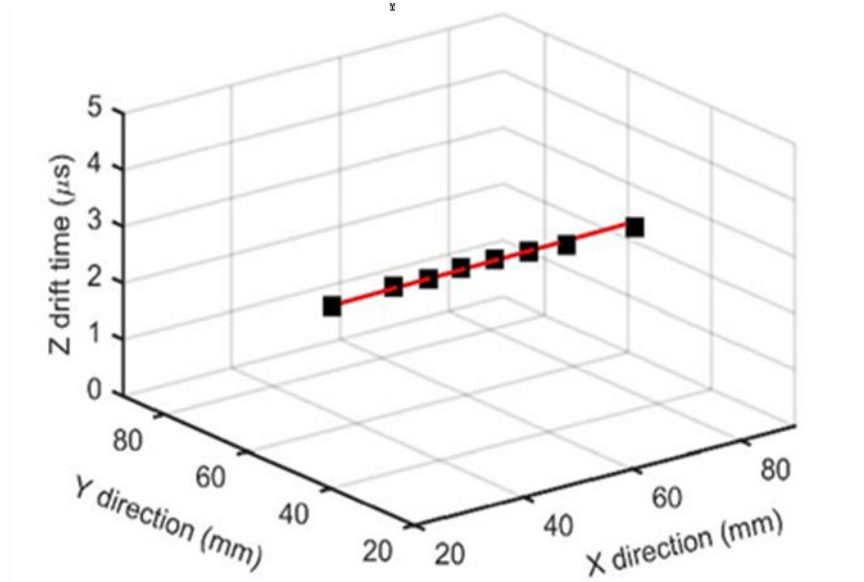


Laser track test







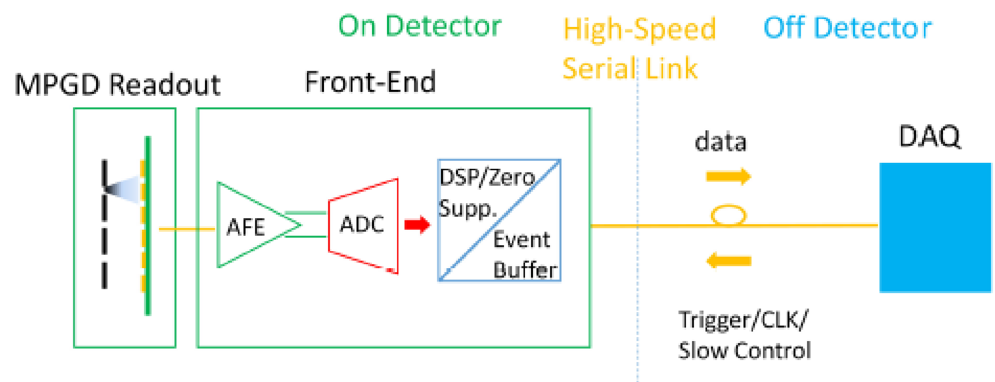


Preliminary results of Laser tracker energy spectrum and tracker

- Low power consumption ASIC

Feasibility study of the low power consumption FEE

- **Each endplate has a total of about 1 million channels**
- **Over 30,000 ASIC chips with 32 channels each**
- **Total power consumption of the front-end electronics is limited by the CO_2 cooling system to be several kilowatts in practice**
- **Two-phase CO_2 cooling/Micro-channel CO_2 cooling methods should be studied further**
- **TPC readout electronics are a few meters away from the collision point, and the radiation dose is rather low (< 1 krad), and radiation sophisticated design needs to be considered too**



Key specifications of the front-end readout ASIC for TPC

Total number of channels		1 million per endcap
AFE (Analog Front-End)	ENC (Equivalent Noise Charge)	500e @ 10pF input capacitance
	Gain	10 mV/fC
	Shaper	CR-RC
	Peaking time	100 ns
ADC	Sampling rate	$\geq$ 20 MSPS
	Resolution	10 bit
Power consumption		$\leq$ 5 mW per channel
Output data bandwidth		300–500 MB/s
Channel number		32
Process		TSMC 65 nm LP

ASIC FEE ASIC chips

- Current TPC readout ASICs

	PASA/ALTRO	AFTER	Super-ALTRO	SAMPA
TPC	ALICE	T2K	ILC	ALICE upgrade
Pad size	4x7.5 mm^2	6.9x9.7 mm^2	1x6 mm^2	4x7.5 mm^2
Pad channels	5.7×10^5	1.25×10^5	$1\text{-}2 \times 10^6$	5.7×10^5
Readout Chamber	MWPC	MicroMegas	GEM/MicroMegas	GEM
Analog Front-end				
Gain	12mV/fC	18 mV/fC	12-27 mV/fC	20/30 mV/fC
Shaper	$CR\text{-}(RC)^4$	$CR\text{-}(RC)^2$	$CR\text{-}(RC)^4$	$CR\text{-}(RC)^4$
Peaking time	200 ns	100 ns	30-120 ns	80/160 ns
ENC	385 e	1000 e	520 e	482 e @ 180ns
Waveform Sampler				
Method	ADC	SCA	ADC	ADC
Sampling frequency	10MSPS	25MSPS	40MSPS	20MSPS
Dynamic range	10bit	10bit	10bit	10bit
Power consumption	32mW/ch	6.2-7.5mW/ch	47.3mW/ch	8mW/ch
CMOS Process	250 nm	350 nm	130 nm	130nm

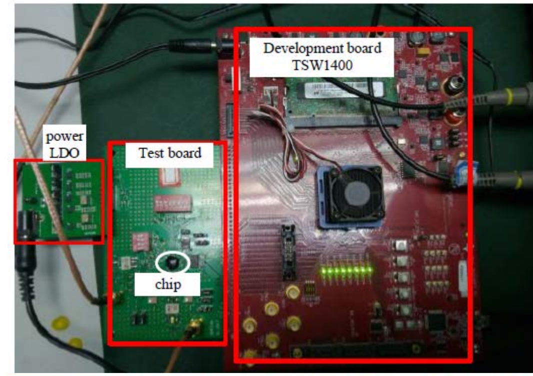
ASIC FEE requirements

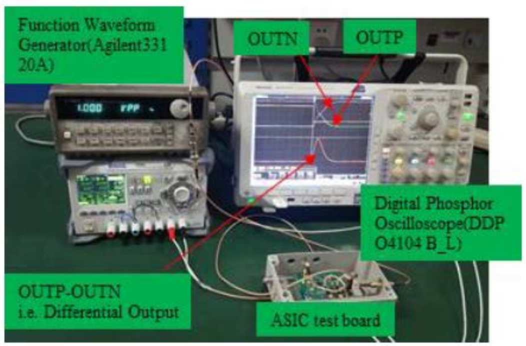
- Requirement for the front-end electronics
  - Analog front-end, including preamplifier and shaper
  - Waveform sampling ADC in 10b and 20-40MSPS
  - Continuous working, no power pulsing → Low power consumption

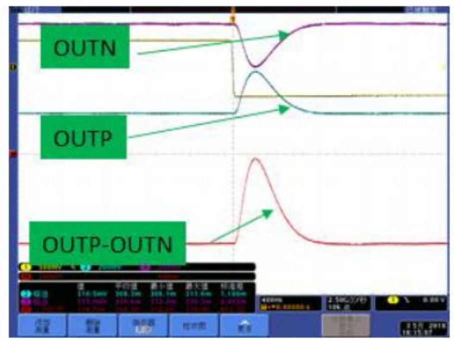
Total number of channels		**~1 Million per endcap**
AFE	ENC	500 e
	Gain	10 mV/fC
	Peaking time	160 ns
ADC	Sampling rate	20-40 MSPS
	Resolution	10 bit
Buffer latency		~50 μs
Data readout rate		20 Gb per event w.o. zero compression
Power consumption		<10 mW per channel
Area		< 6 mm^2 per channel, incl. cooling

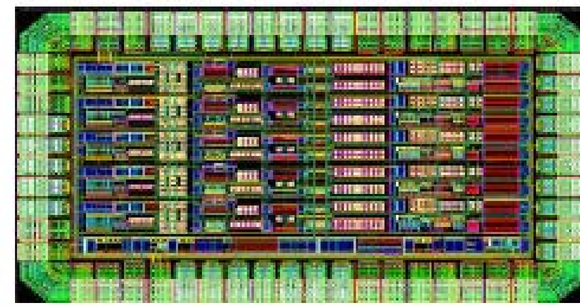
Results of FEE ASIC

- Develop a low power and highly integration front-end ASIC in 65 nm CMOS
- Each channel consists of the analog front-end (AFE) and a SAR ADC in 10b and up to 40 MSPS
- Less than 5 mW per channel









1320um x 838um

- AFE test summary

	Specifications	Test Results
Gain	10mV/fC	10.5mV/fC
Dynamic Range	120fC	>120fC
INL	<1%	0.41%
Power consumption	2.50mW/ch	2.18mW/ch
ENC	500e @ 10pF	448e @ 10pF
Xtalk	<1%	<0.36%

- SAR ADC test summary

	Specifications	Test Results
Sampling rate	40 MSPS	50 MSPS
Resolution	10 bit	10 bit
INL	<0.65 LBS	<0.5 LSB
DNL	<0.6 LSB	<0.5 LSB
ENOB	>9 bit	9.18 bit
Power consumption	<2.5 mW/ch	1 mW/ch

Summary and further R&D

Requirements and critical challenges for CEPC:

- **High momentum resolution and position resolution**
- **Continuous beam structure and the ~25ns time space**

Continuous IBF module for CEPC:

- **Continuous Ion Back Flow supression**
- **Key factor: IBF×Gain=5 and leas than (R&D)**
- **Low discharge and the good energy spectrum**

Prototype with laser calibration for CEPC :

- **It needs very sophisticated calibration in order to reach the desired physics performance at Z pole run**
- **Prototype has been designed with laser (Developed in IHEP and Tsinghua)**

Low power consumption ASIC chip:

- **FEE electronics and DAQ collaborated with Tsinghua University**
- **Less than 5mV per channel**

Thanks.