Review of TPC Detector R&D for CEPC CDR

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Outline

- Motivation in CEPC CDR
- TPC detector module and prototype
- FEE electronics ASIC chip
- Summary

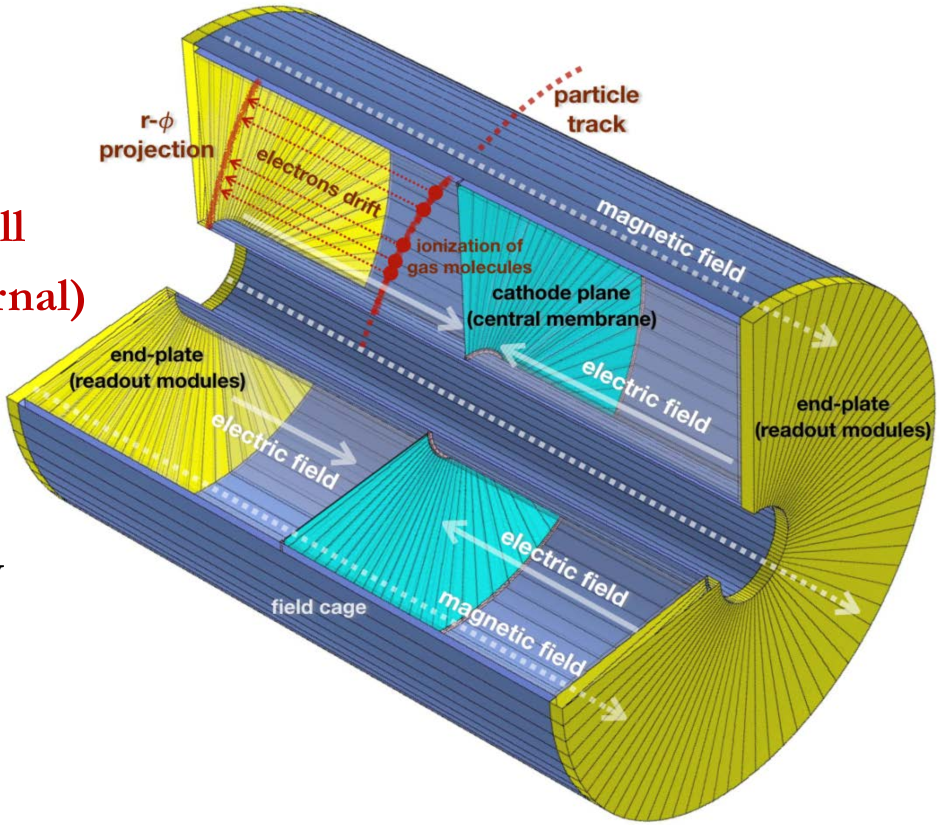
- Motivation in CEPC CDR

TPC requirements for collider concept

TPC could be as one tracker detector option for CEPC, 1M ZH events in 10yrs E_{cm} ≈240 GeV, luminosity ~2×10^{34} $cm^{-2}s^{-1}$, can also run at the Z-pole

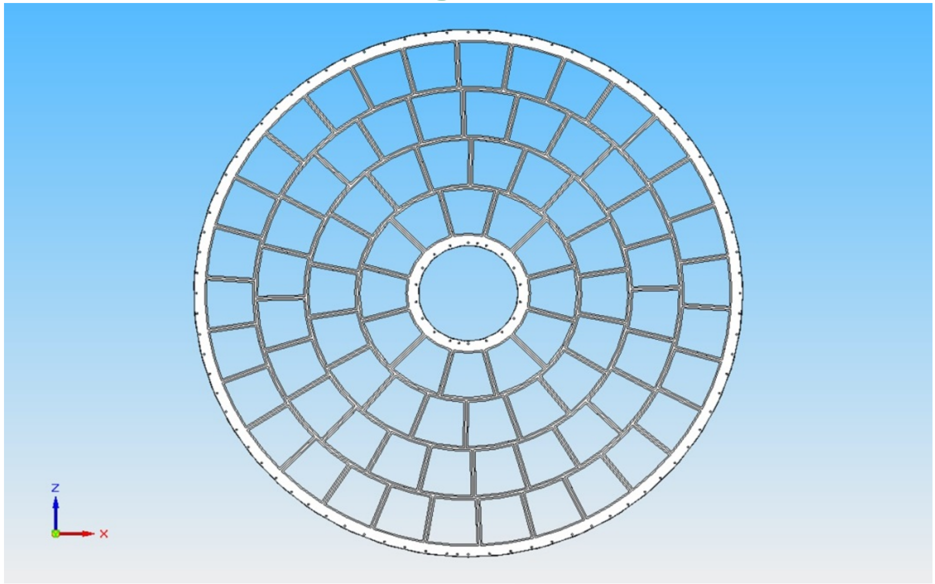
TPC detector concept:

- **Motivated by the H tagging and Z**
- **~3 Tesla magnetic field**
- **~100 μm position resolution in rφ**
  - ~60μm for zero drift, <100μm overall
  - Systematics precision (<20μm internal)
- **Large number of 3D points(~220)**
- **Distortion by IBF issues**
- dE/dx resolution: <5%
- **Tracker efficiency: >97% for pT>1GeV**
- 2-hit resolution in rφ : ~2mm
- **Momentum resolution: ~10^{-4}/GeV/c**
- **TPC material budget**
  - 0.05 X_0 including outer fieldcage in r
  - 0.25 X_0 for readout endcaps in z

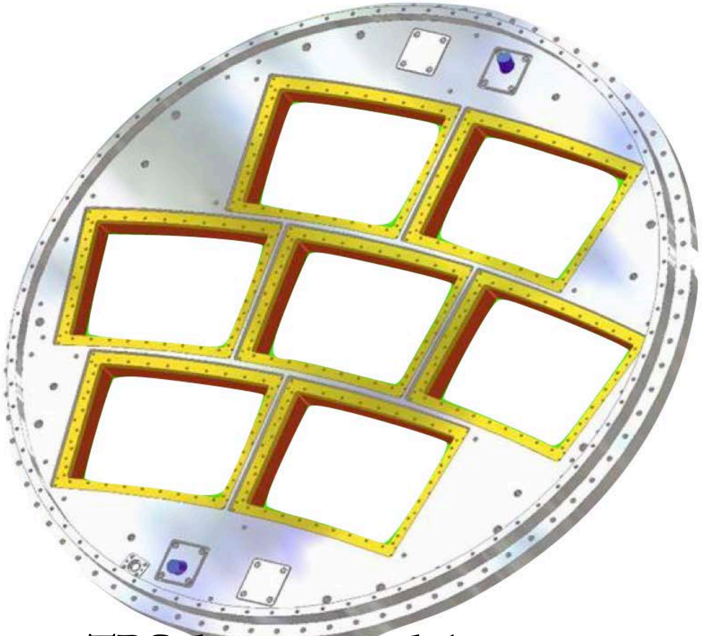


Overview of TPC detector concept

TPC with MPGDs as readout /Advantage



- Higher accuracy < 100mm(Overall along the drift)
- Better two track resolution
- Full 3-D track reconstruction
- Precise dE/dX
- High magnetic field (>3T)
- Highly reduced E×B effect
- Large detectors by industrial process
- Easy assembled using the modules
- Minimal material budget
- Much higher Ion feed back suppression
- Drift time gives the longitudinal coordinate



TPC detector module concept

CEPC Detector for CDR

Baseline design parameters

Feasibility & Optimized Parameters

√Feasibility analysis: TPC and Passive Cooling Calorimeter is valid for CEPC

	CEPC_v1 (~ ILD)	Optimized (Preliminary)	Comments
Track Radius	1.8 m	>= 1.8 m	Requested by Br(H->di muon) measurement
B Field	**3.5 T**	**3 T**	**Requested by MDI**
ToF	**-**	**50 ps**	**Requested by pi-Kaon separation at Z pole**
ECAL Thickness	84 mm	84(90) mm	84 mm is optimized on Br(H->di photon) at 250 GeV;
ECAL Cell Size	5 mm	10 – 20 mm	Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation
ECAL NLayer	30	20 – 30	Depends on the Silicon Sensor thickness
HCAL Thickness	**1.3 m**	**1 m**	-
HCAL NLayer	**48**	**40**	Optimized on Higgs event at 250 GeV;

Three key issue questions in CEPC CDR

- Occupancy: at inner diameter
  - Low occupancy
  - Overlapping tracks
  - Background at IP

Simulation

TPC as one option for CPEC YES or NO?

- Ion Back Flow
  - Continuous beam structure
  - Long working time with low discharge possibility
  - Necessary to fully suppress the space charge produced by ion back flow from the amplification gap

Simulation + R&D

To control IONS?
To reduce distortion

- Calibration and alignment
  - Complex MDI design
  - Laser calibration system

Simulation + R&D

~100um positron resolution with calibration?

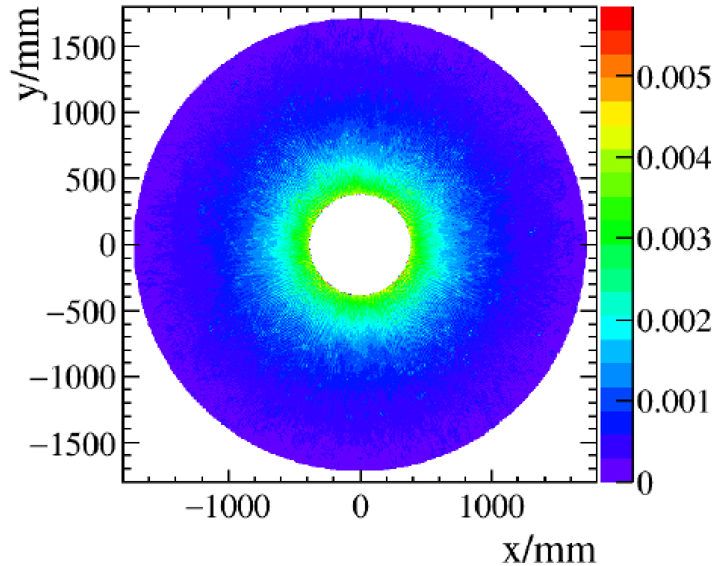
High rate at Z pole

ArXiv: 1704.04401

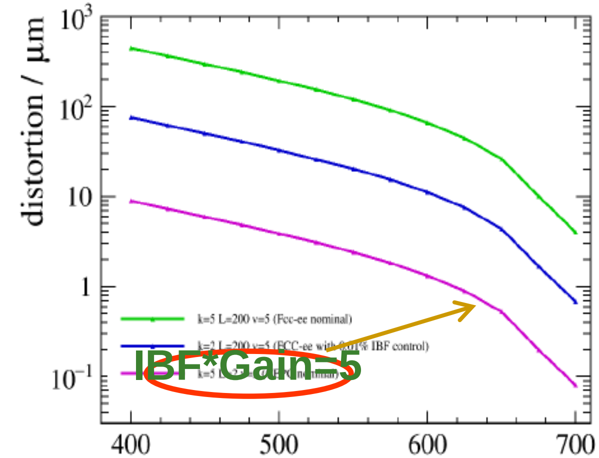
Mingrui, Manqi, Huirong

- Voxel occupancy
  - The number of voxels / signal
  - 9 thousand Z to qq events
  - 60 million hits are generated in sample
  - 4000-6000 hits/(Z to qq) in TPC volume
  - Average hit density: 6 hits/mm^2
  - Peak value of hit density: 6 times
  - Voxel size: 1mm $\times$ 6mm $\times$ 2mm
  - 1.33×10^{14} number of voxels/s @DAQ/40MHz
  - Average voxel occupancy: 1.33×10^{-8}
  - Voxel occupancy at TPC inner most layer: $\sim 2 \times 10^{-7}$
  - Voxel occupancy at TPC inner inner most layer : $\sim 2 \times 10^{-5}$ @FCCee benchmark luminosity

The voxel occupancy takes its maximal value between 2×10^{-5} to 2×10^{-7}, which is safety for the Z pole operation.

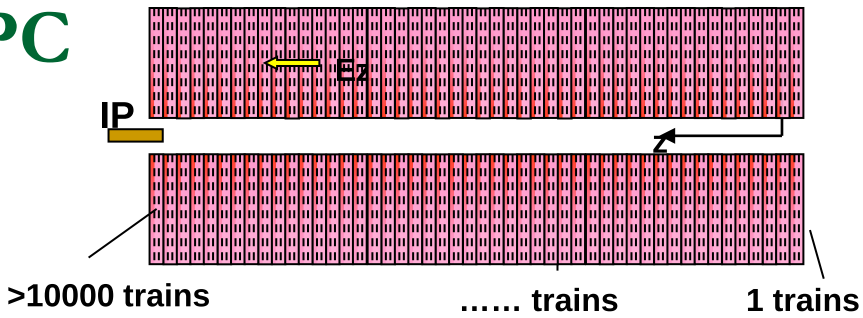


Hit map on X-Y plan for Z to qq events



Distortion of as a function of electron initial r position

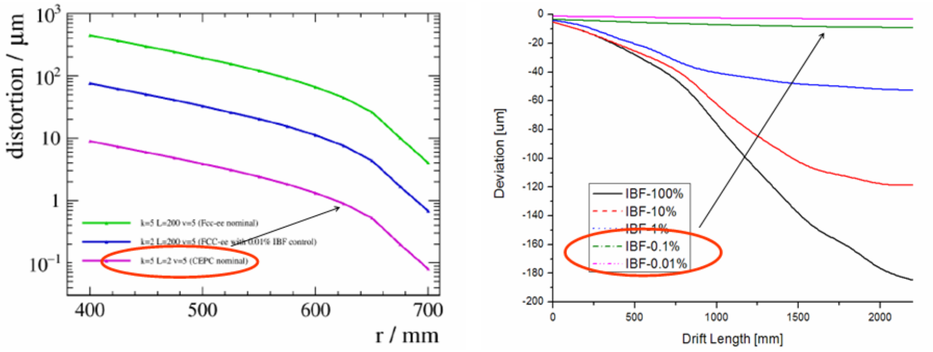
Technical challenges for TPC



Amplification ions @CEPC

Ion Back Flow and Distortion :

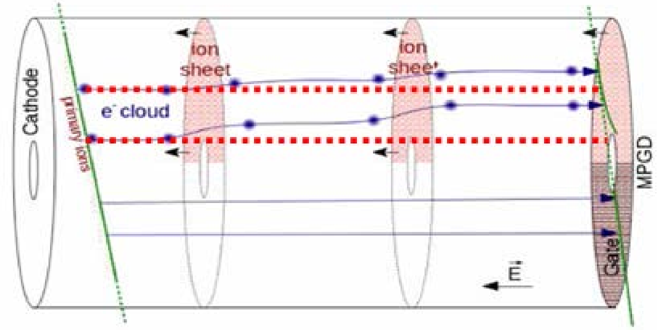
- ~100 μm position resolution in rφ
- Distortions by the primary ions at CEPC are negligible
- More than 10000 discs co-exist and distorted the path of the seed electrons
- The ions have to be cleared during the ~us period continuously
- Continuous device for the ions
- Long working time



Evaluation of track distortions

Calibration and alignment:

- Systematics precision (<20 μm internal)
- Geometry and mechanic of chamber
- Modules and readout pads
- Track distortions due to space charge effects of positive ions

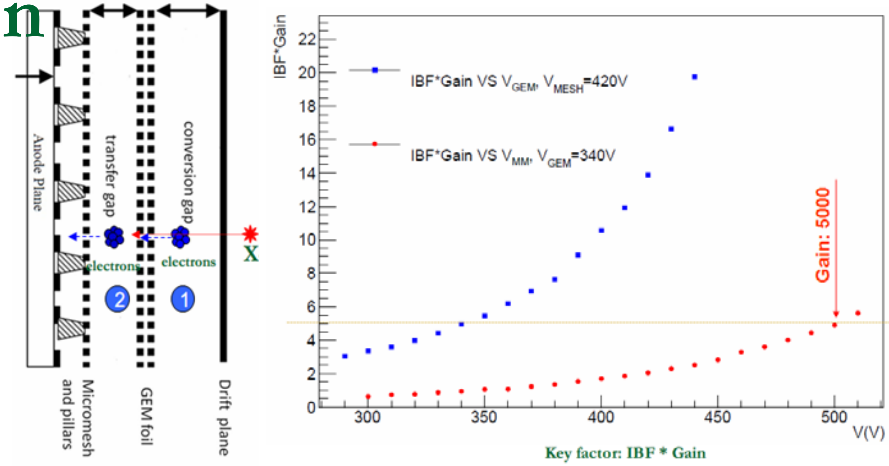


Ions backflow in drift volume for distortion

Options of technical solution

Continuous IBF module:

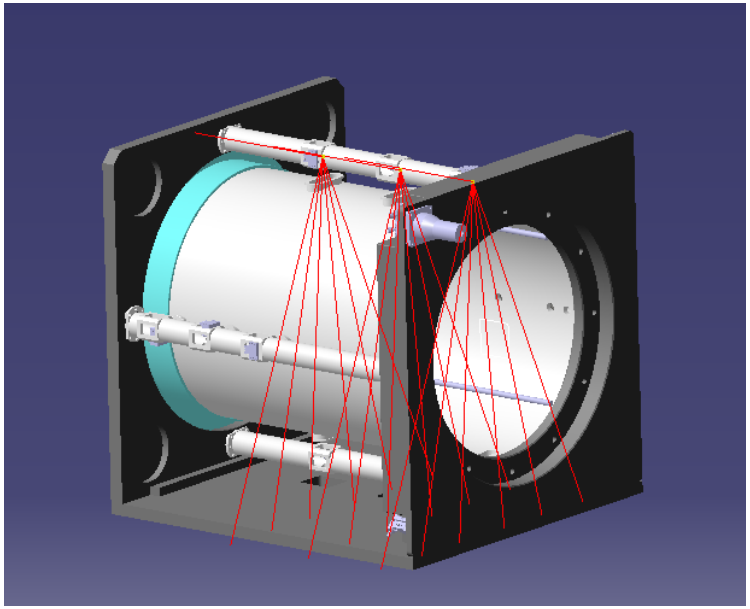
- Gating device may be used for Higgs run
- Open and close time of gating device for ions: ~ µs-ms
- No Gating device option for Z-pole run
- Continuous Ion Back Flow due to the continuous beam structure
- Low discharge and spark possibility



Continuous IBF prototype and IBF × Gain

Laser calibration system:

- Laser calibration system for Z-pole run
- The ionization in the gas volume along the laser path occurs via two photon absorption by organic impurities
- Calibrated drift velocity, gain uniformity, ions back in chamber
- Calibration of the distortion
- Nd:YAG laser device@266nm

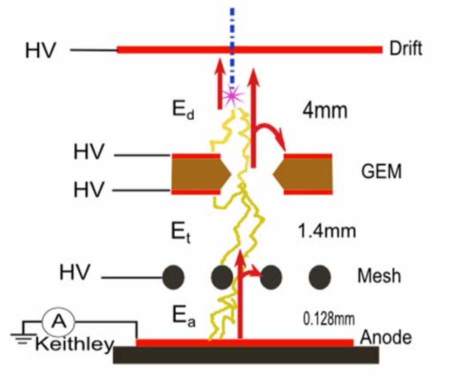


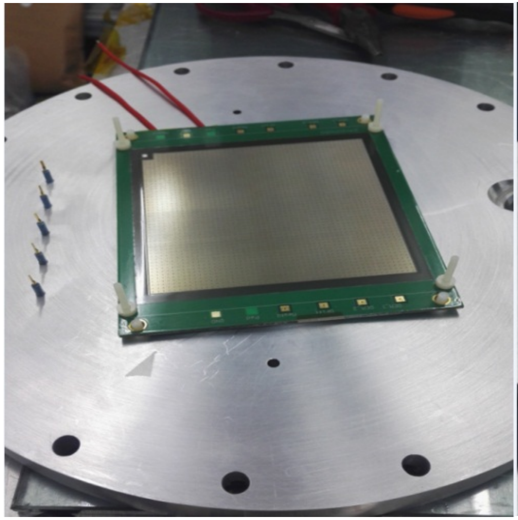
TPC prototype integrated with laser system

- Ions backflow reduced
- TPC detector module R&D
  - Combination detector
  - Discharge for IBF

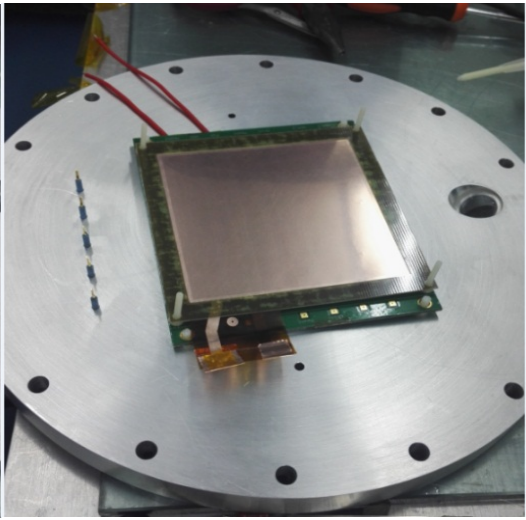
Test of the new module

- Test with GEM-MM module
  - New assembled module
  - Active area: 100mm×100mm
  - X-tube ray and 55Fe source
  - Bulk-Micromegas from Saclay
  - Standard GEM from CERN
  - Additional UV light device
  - Avalanche gap of MM:128μm
  - Transfer gap: 2mm
  - Drift length:2mm~200mm
  - Mesh: 400LPI

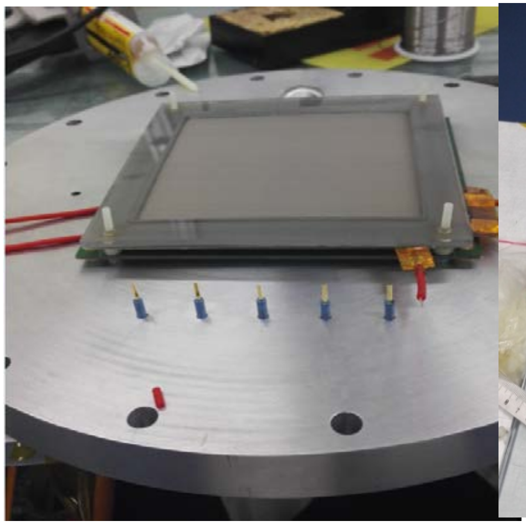




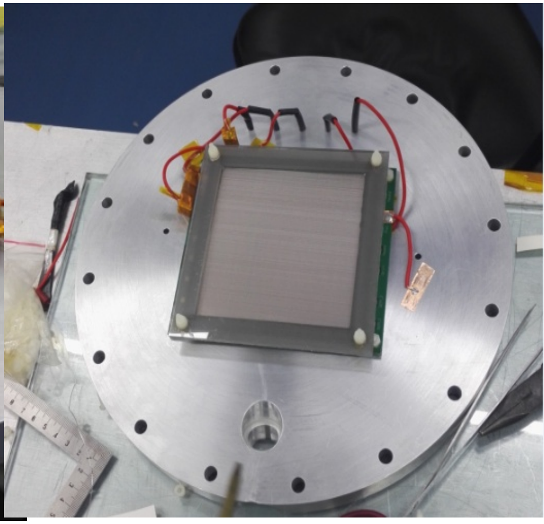
Micromegas(Saclay)



GEM(CERN)



Cathode with mesh

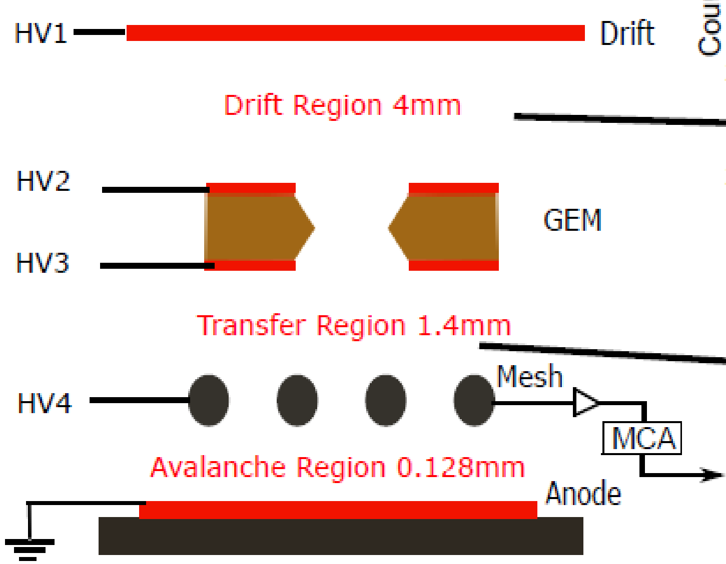


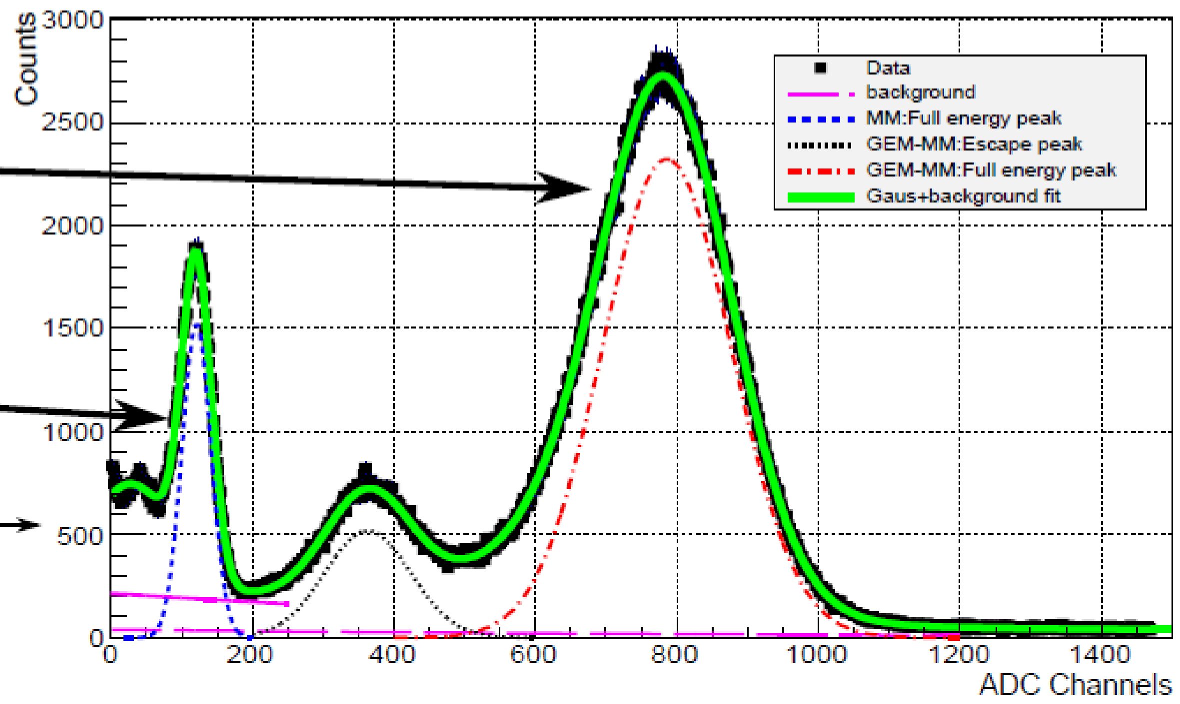
GEM-MM Detector

GEM+MM@CEPC R&D

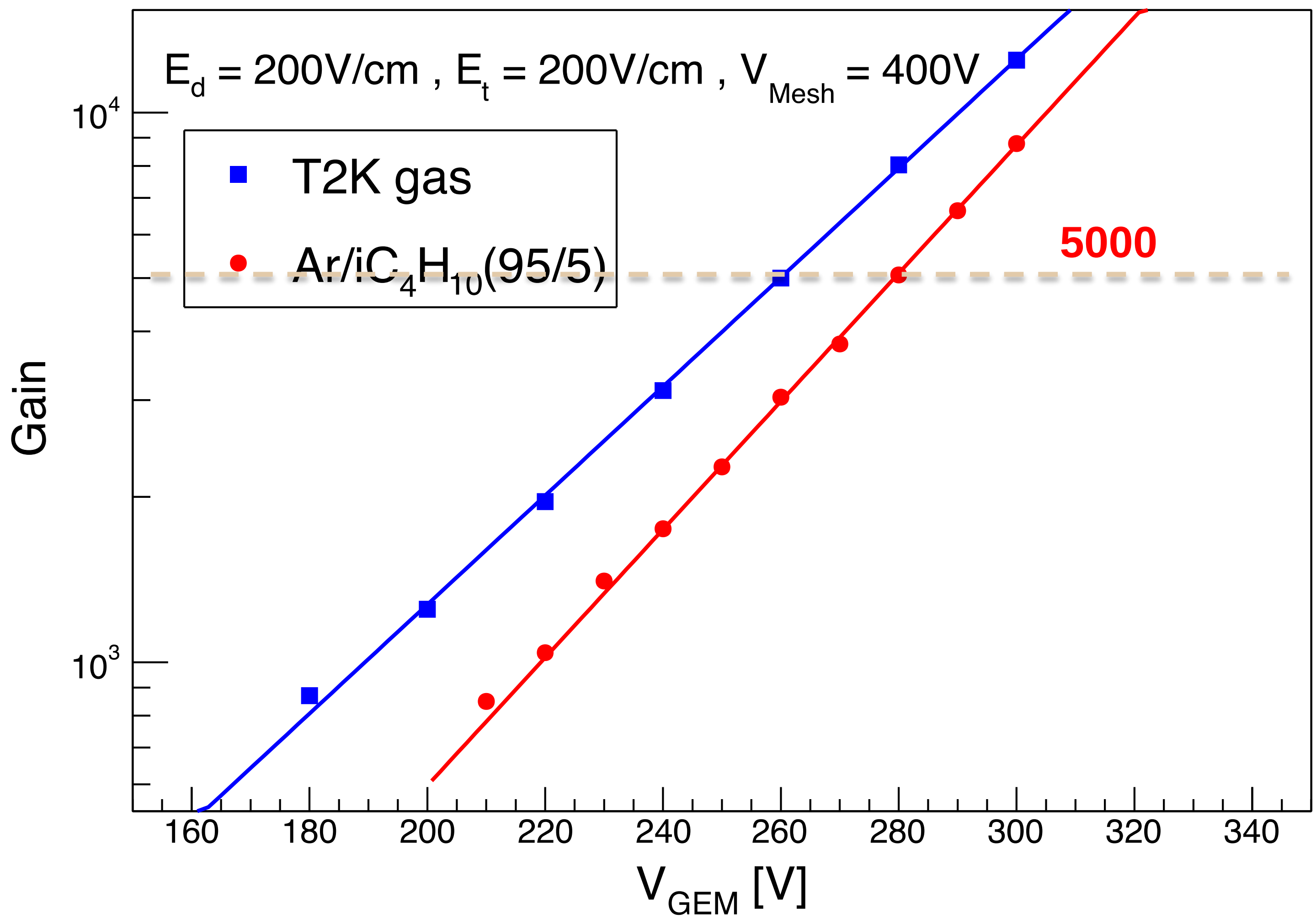
e+e- machine
Primary N_{eff} is small: ~30
Pad size:1mm×6mm

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

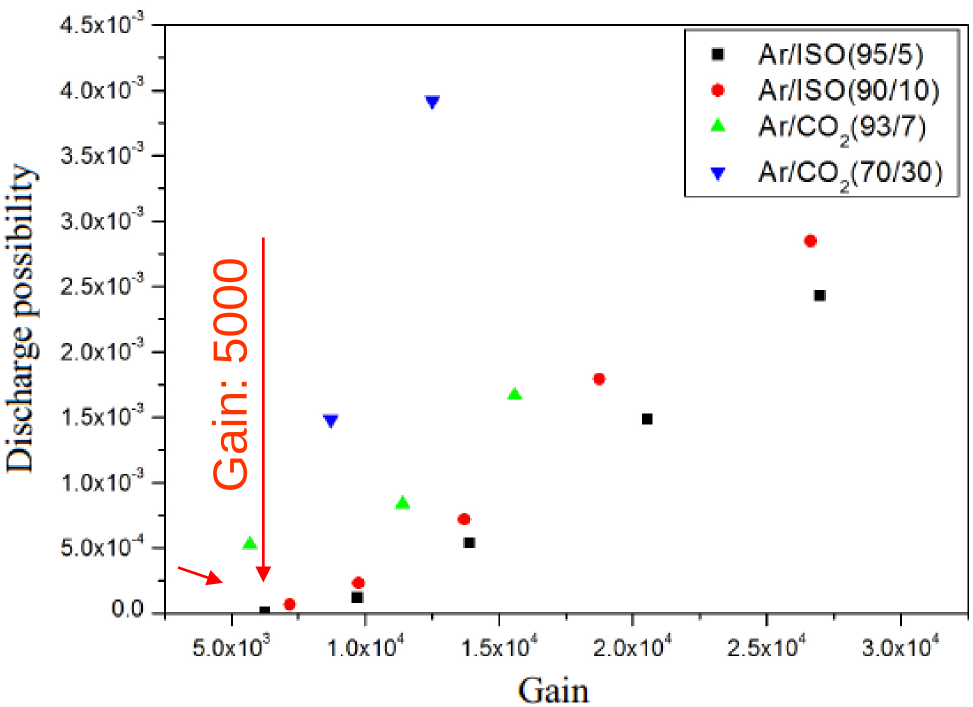


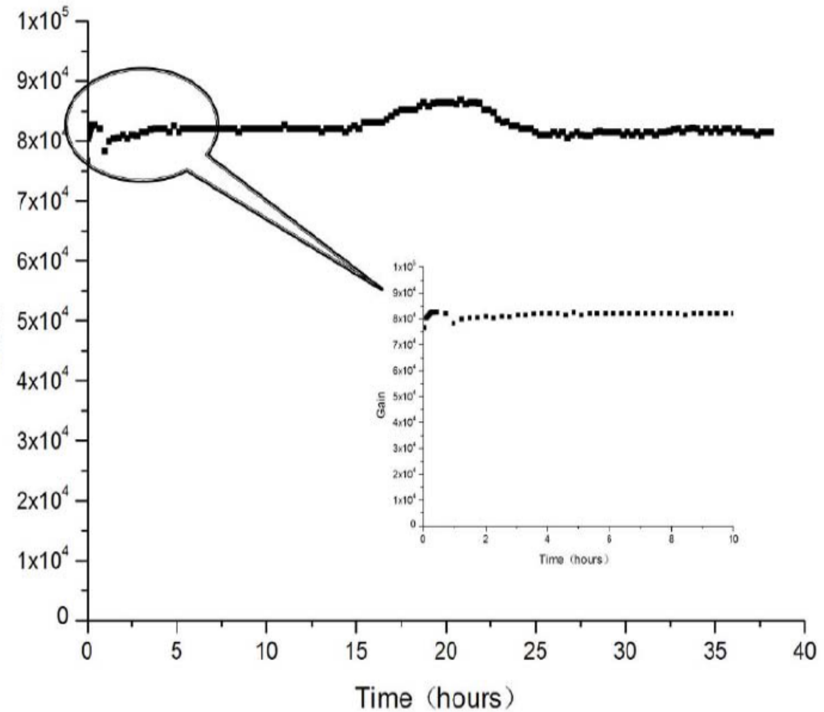


Gain of the hybrid structure detector



Discharge and working time





- Test with Fe-55 X-ray radiation source
  - Discharge possibility could be mostly reduced than the standard Bulk-Micromegas
  - Discharge possibility of hybrid detector could be used at Gain~10000
  - To reduce the discharge probability more obvious than standard Micromegas
  - At higher gain, the module could keep the longer working time in stable

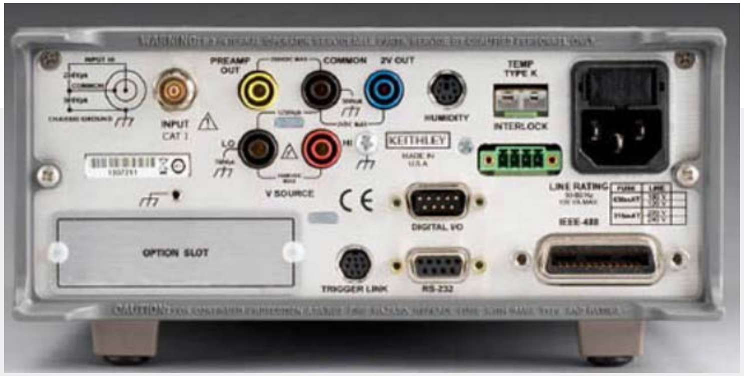
Electrometer/High Resistance Meter

Keithley 6517B

Electrometer/High Resistance Meter, 100aA - 20mA, 10μV - 200V, 100Ω - 10PΩ

Brand:	Keithley
Model No:	6517B

KEITHLEY
A Tektronix Company

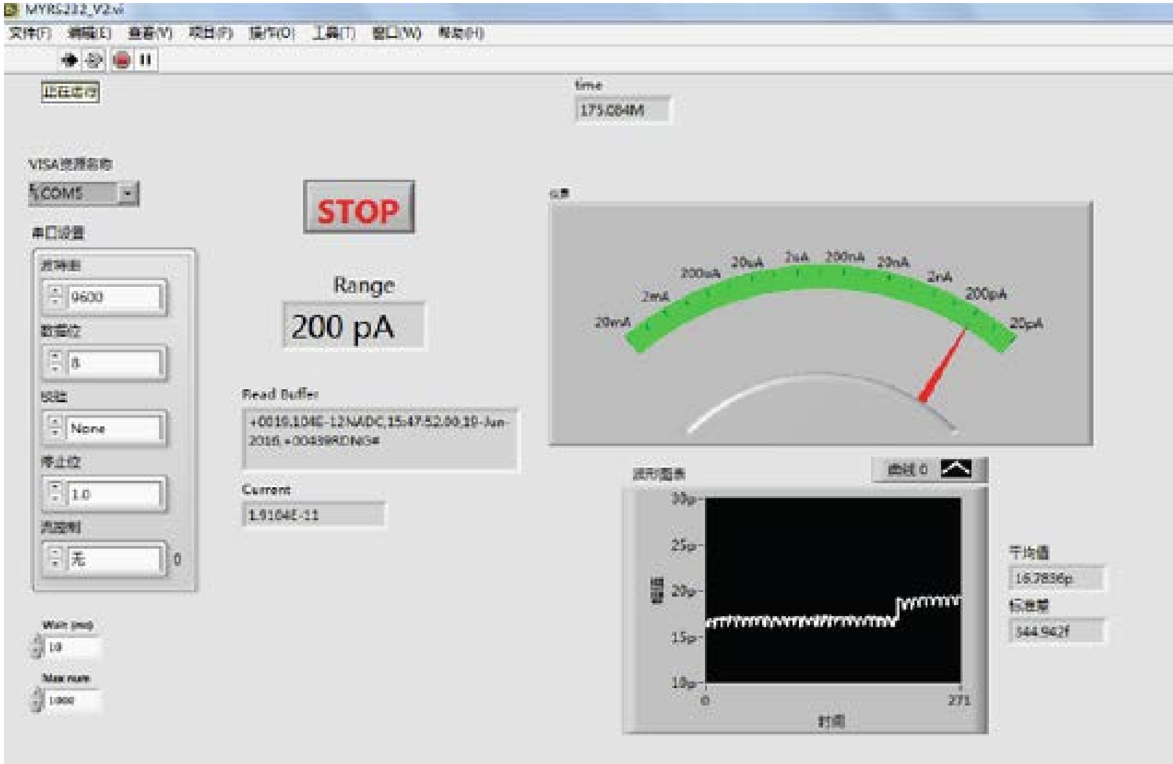


Product Features:

- Measures resistances up to 1018O
- 10aA (10×10-18A) current measurement resolution
- Less than 3fA input bias current
- 6 1/2-digit high accuracy measurement mode
- Less than 20μV burden voltage on the lowest current ranges
- Voltage measurements up to 200V with >200TO input impedance
- Built-in +/-1000V voltage source
- Unique alternating polarity voltage sourcing and measurement method for high resistance measurements
- Built-in test sequences for four different device characterization tests, surface and volume resistivity, surface insulation resistance, and voltage sweeping
- Optional plug-in scanner cards for testing up to 10 devices or material samples with one test setup

Measuremnt of GEM-MM module

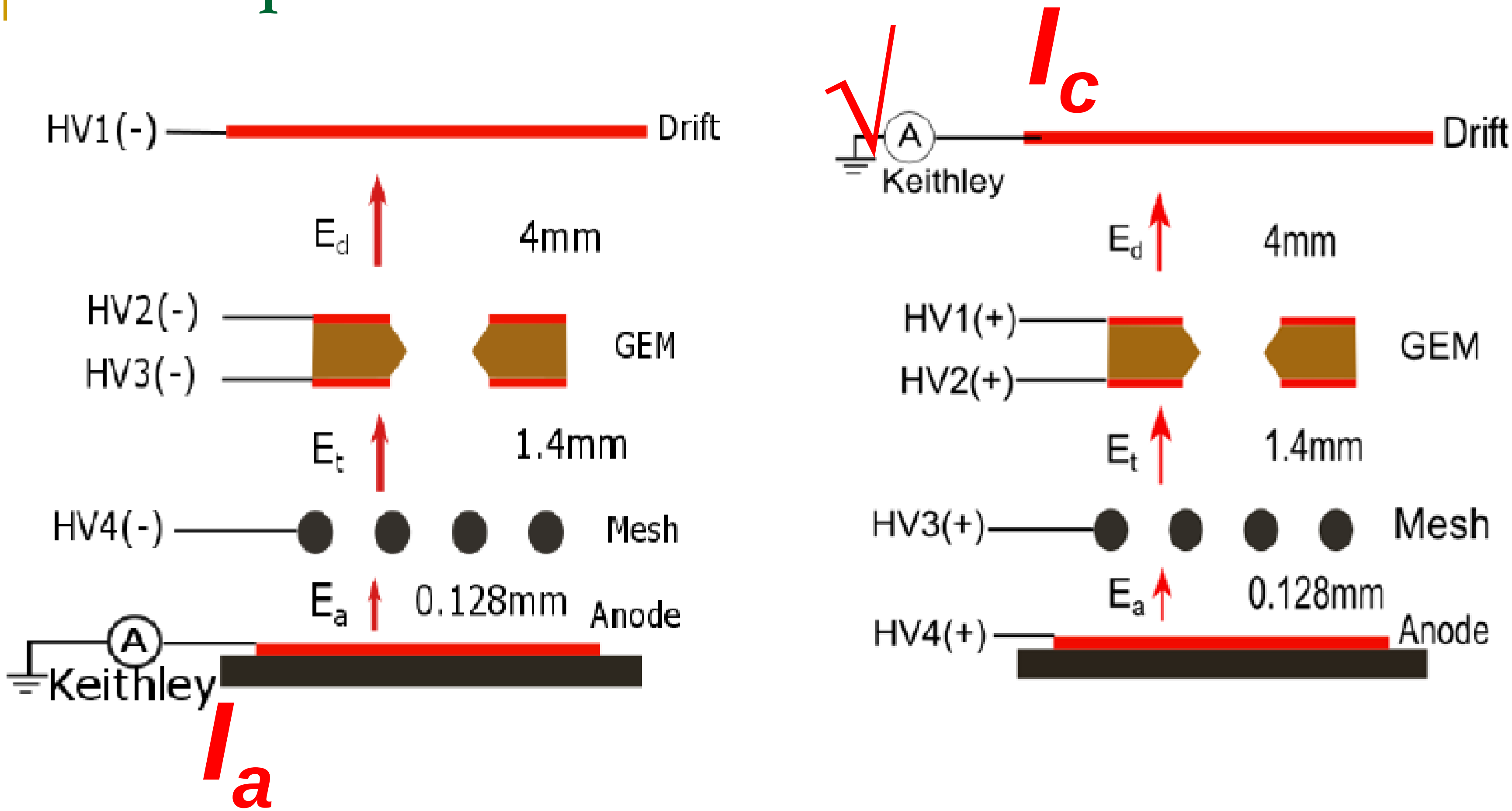
- Test with GEM-MM module
  - Keithley Electrometers for Ultra-Low Current Measurements: pA~mA
  - Keithley: 6517B
  - Test of cathode of the module
  - Test of readout anode of the module
  - Labview interface of the low current to make the record file automatically



Labview interface of the current with Keithley

$$IBF = \frac{I_C - I_P}{I_A}$$

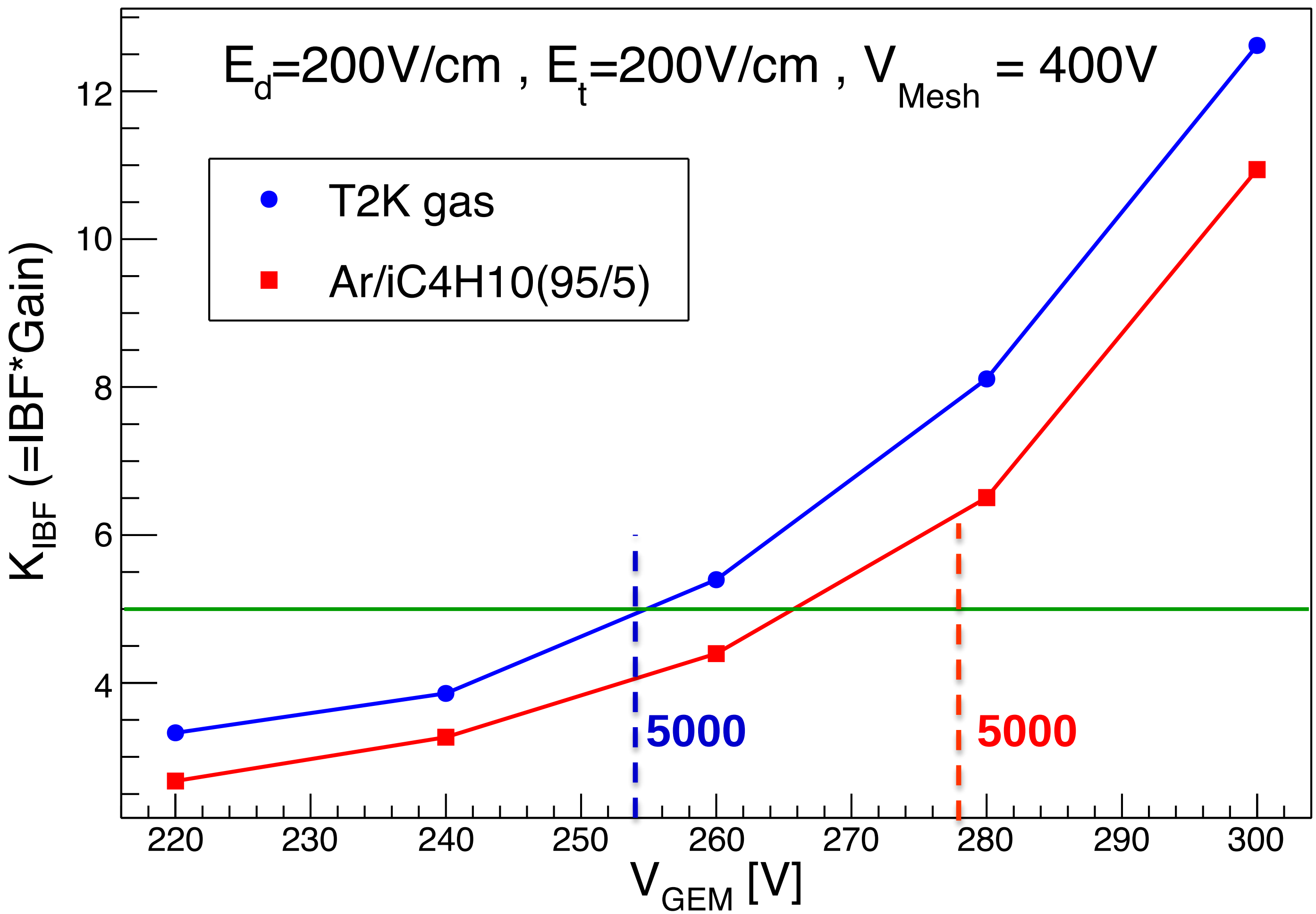
Two steps



- Different polarity
- Same electric filed
  - Ed=Ed; Et=Et; Ea=Ea

Key IBF factor: IBF×Gain

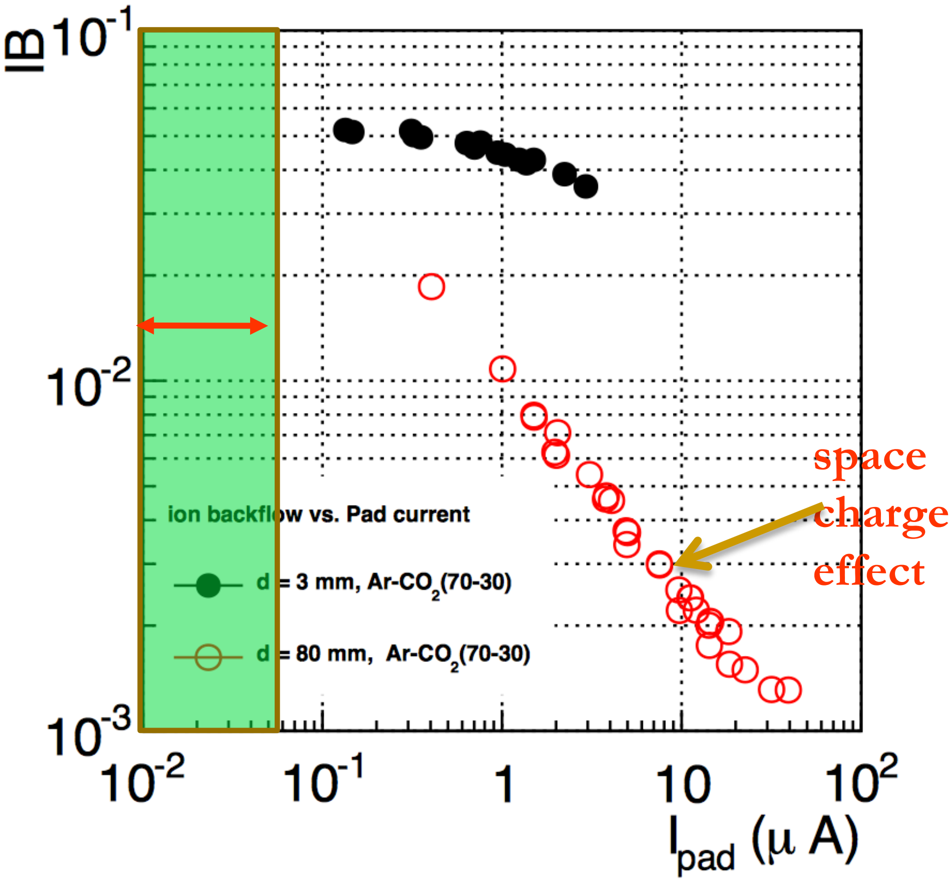
Preliminary results in 2018

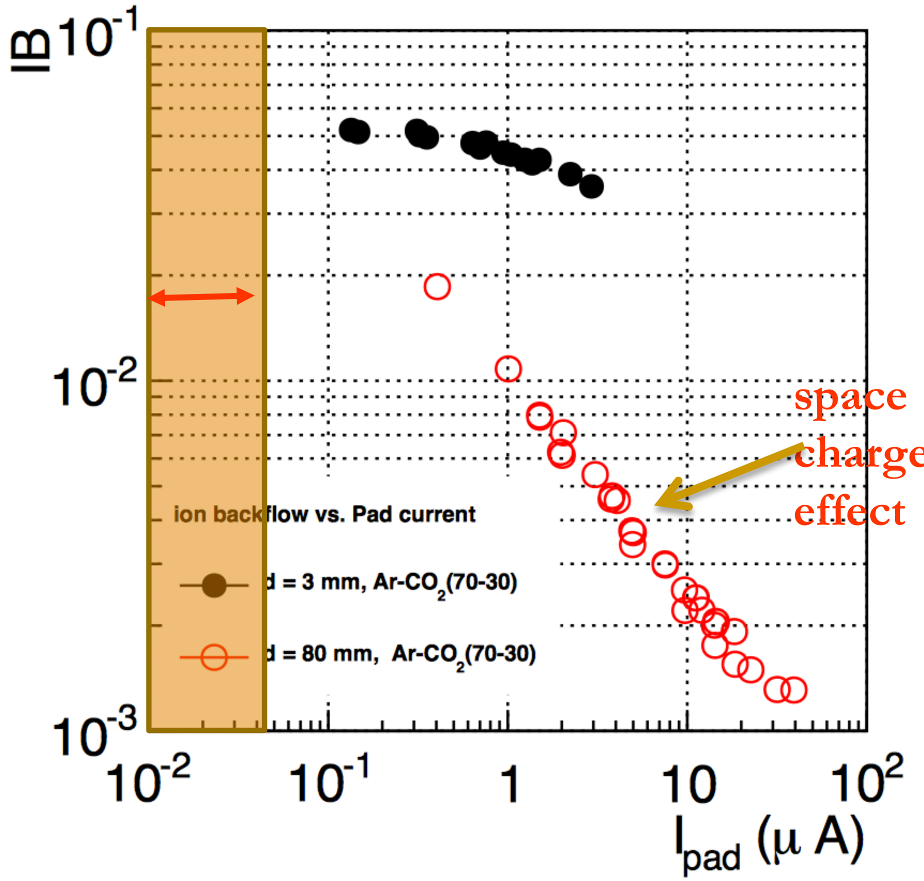


- Space charge effect for IBF

Check and answer- I_{pad}

Current of Pad is very low in our Exp.
No space charge effect

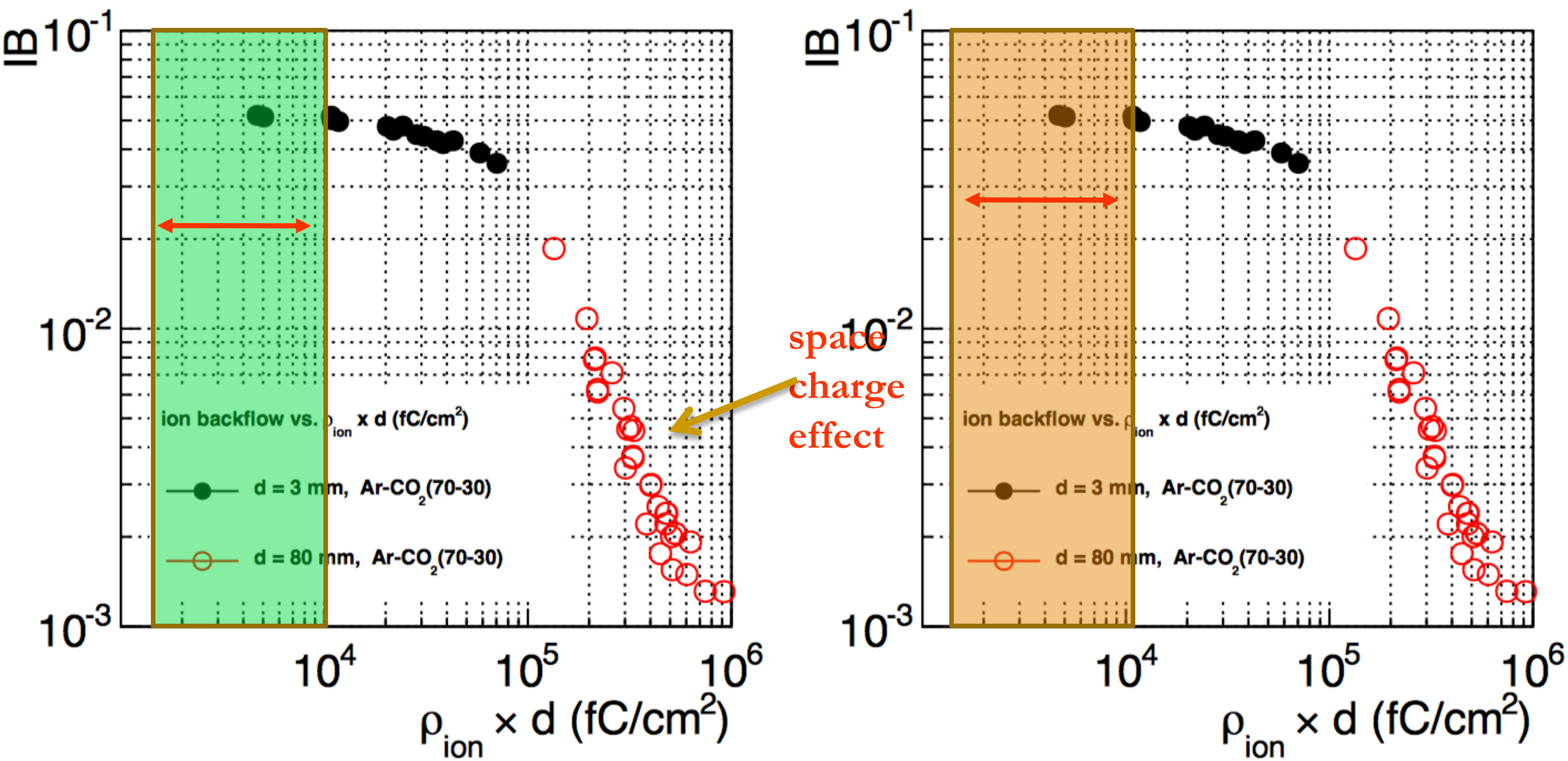




Green， T2K， Et=200V/cm, Ed=200V/cm, V_mesh=400V, V_Gem:30~300V
Yellow， Ar/iso(95/5) ， Et=200V/cm, Ed=200V/cm, V_mesh=400V, V_Gem:30~300V

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

Current of Pad is very low in our Exp.
No space charge effect



Green: T2K， Yellow: Ar/iso(95/5)

T2Kgas Ic: 4pA～59pA， ～10^3 （fC/cm²）
Ar/iso gas Ic : 3.5pA~53pA, ～10^3 （fC/cm²）

- **Calibration** (Drift velocity/Uniformity/Distortion)
- **TPC detector prototype R&D**
  - Signal of the 266nm laser beam @MPGD
  - Stability of the position@100um resolution
  - Stability of the energy @ASIC FEE

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

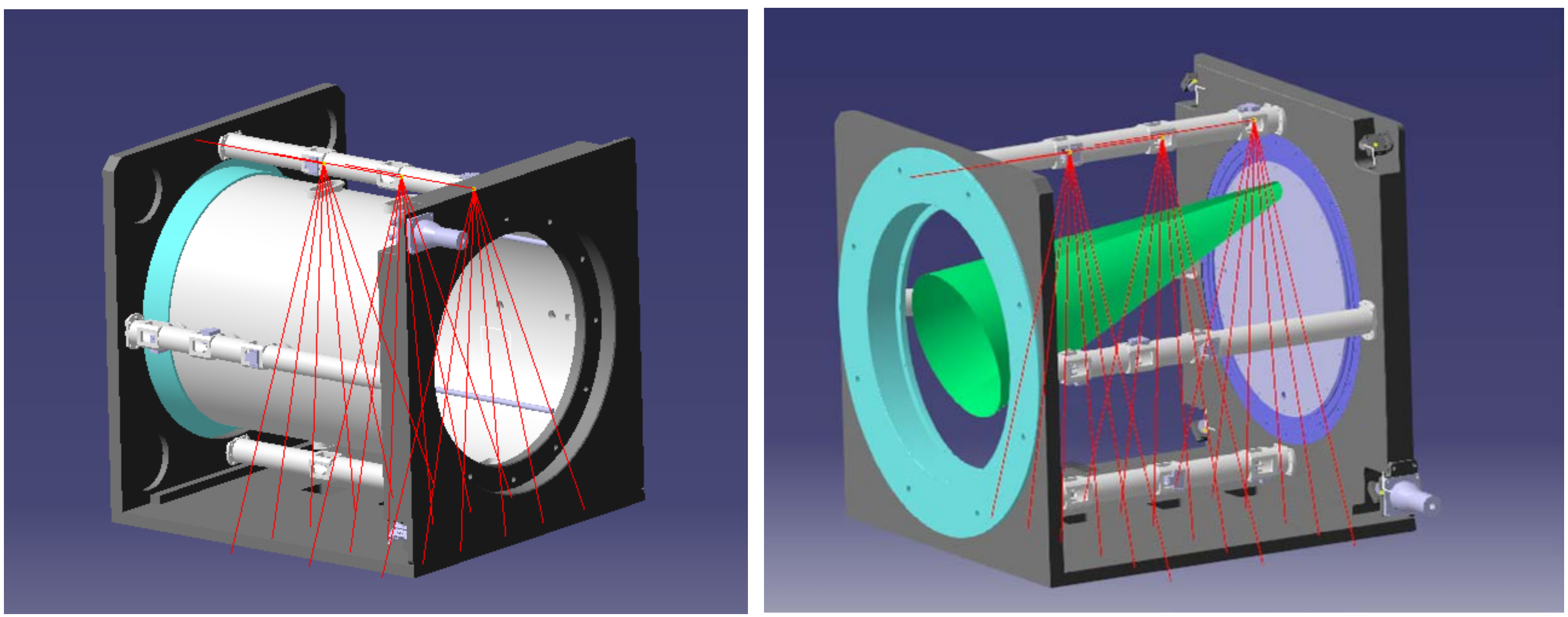
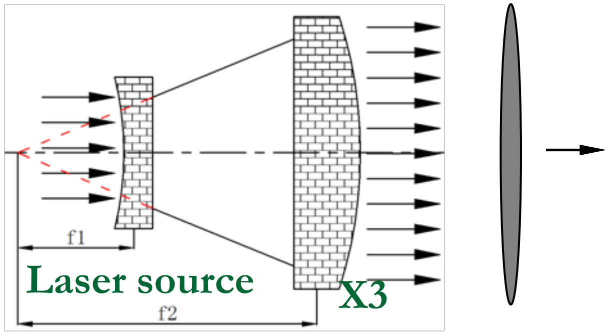
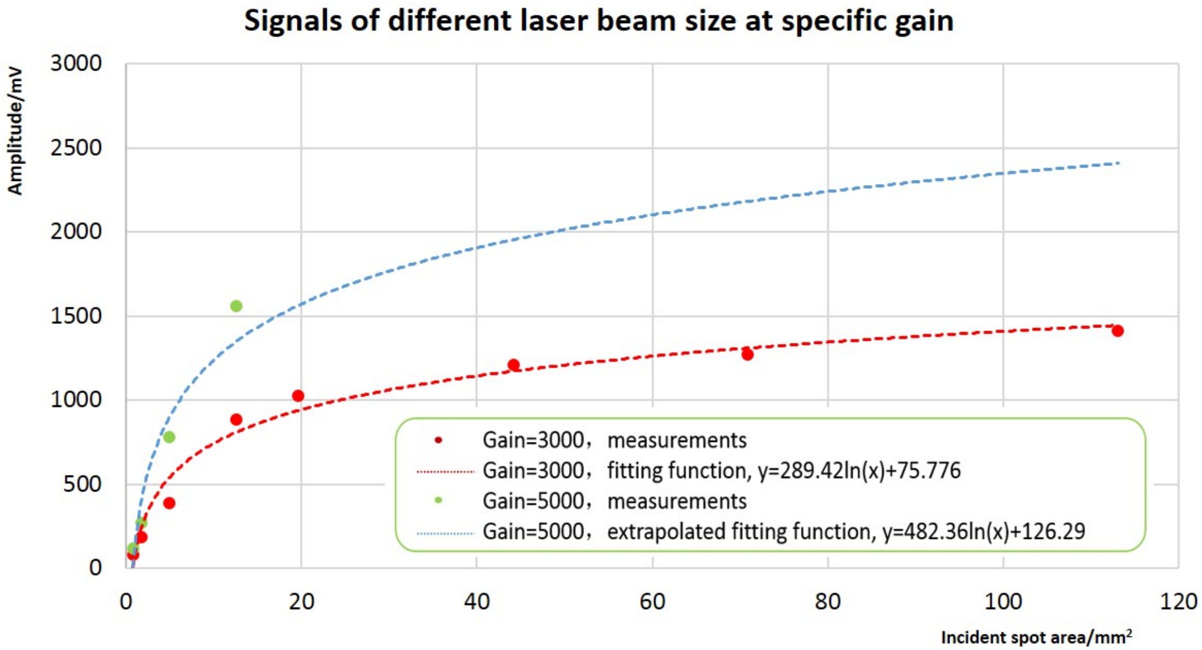


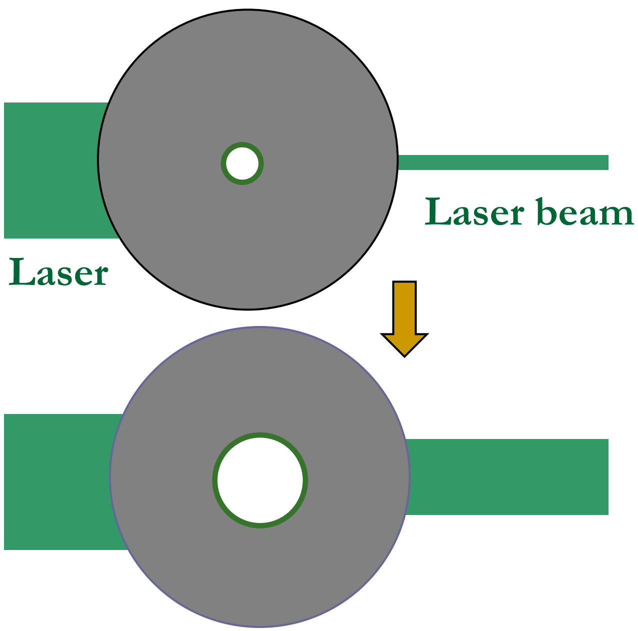
Diagram of the TPC prototype with the laser calibration system

Collimator for the laser beam@Φ1~ Φ 12mm

- Laser beam with expander mirror: 5mm×3
- Primary laser power: 170uJ
- Gain:~3000/5000





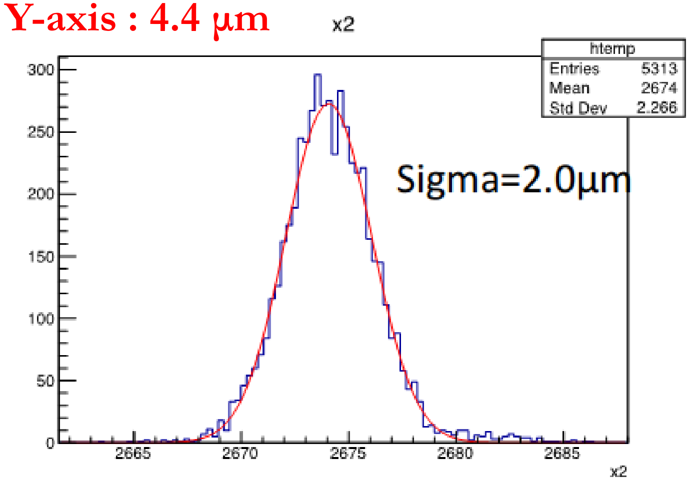


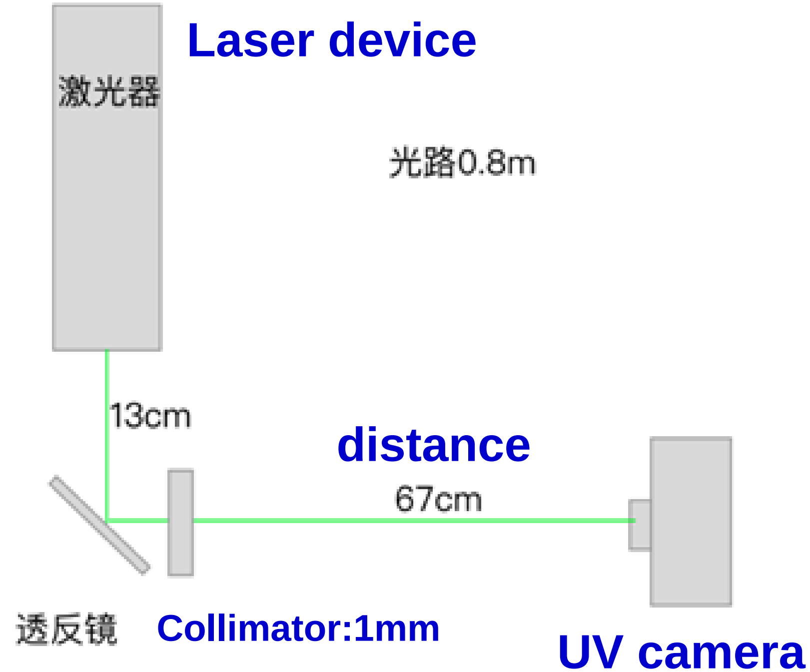
Area of laser beam in detector

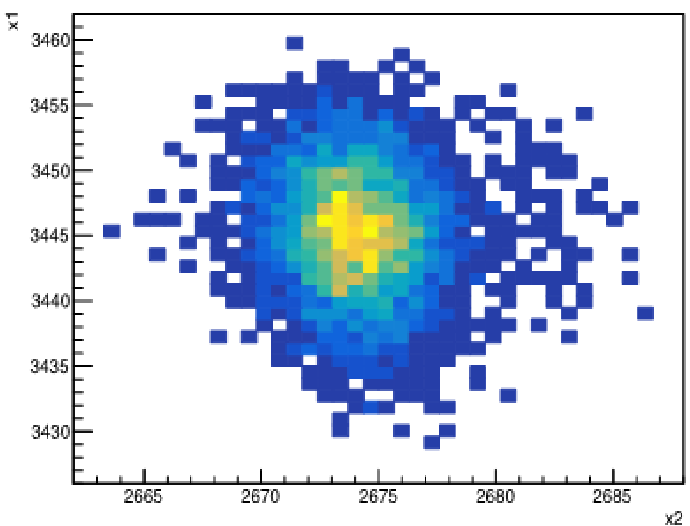
Stability of the laser beam position

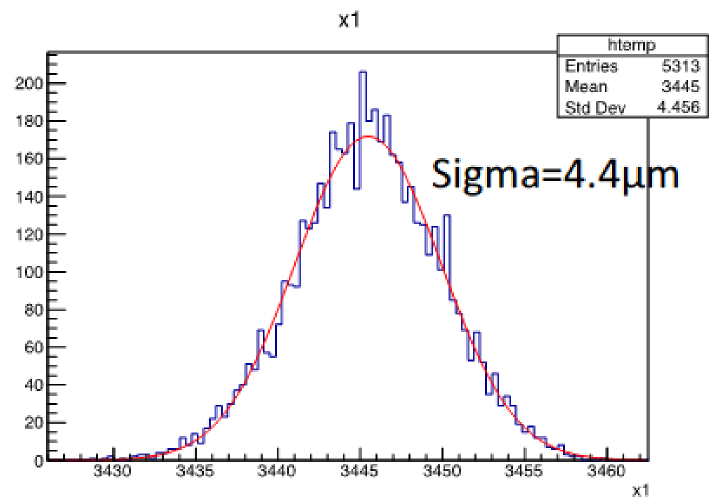
GOOD !

- Duration of measurement time: 10mins
- Stability of the laser beam energy
  - X-axis : 2.0 μm
  - Y-axis : 4.4 μm





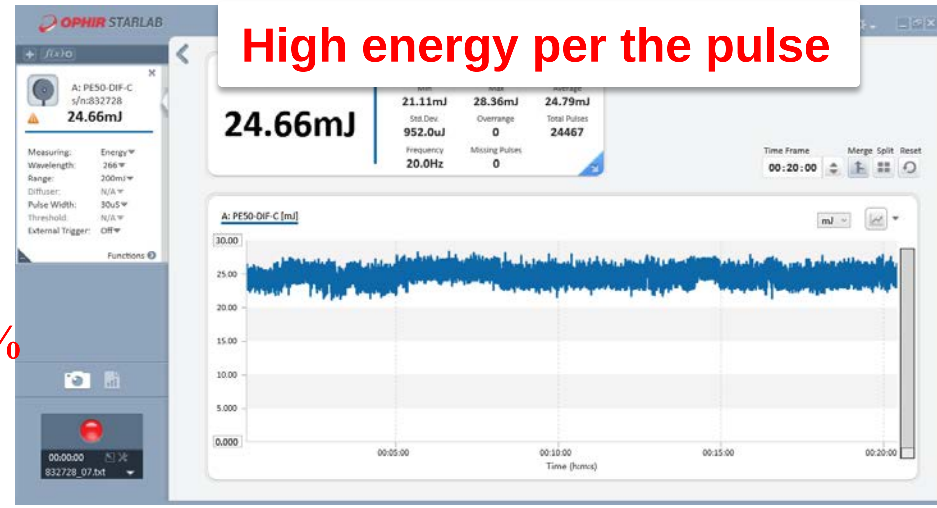




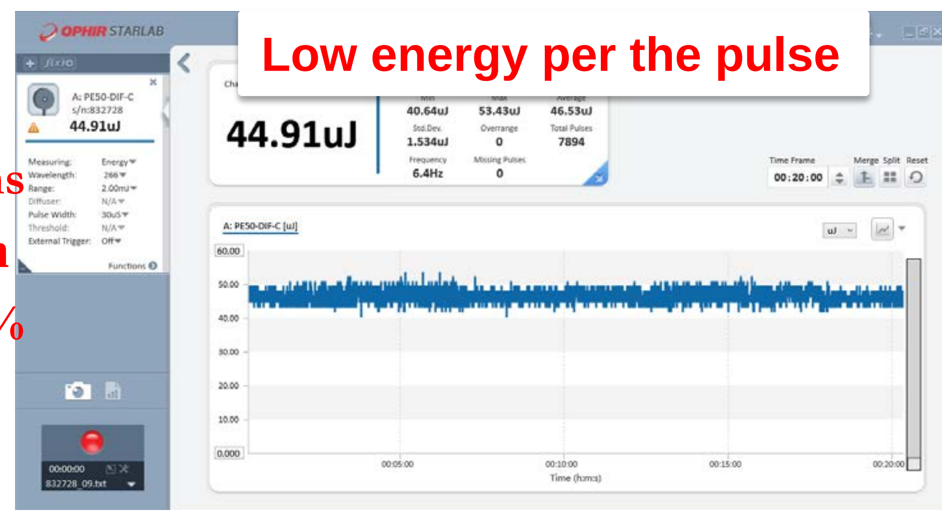
Stability of the laser beam energy

GOOD !

- Duration of measurement time: 20mins
- Average of the energy: 24.79mJ/Φ5mm
- Stability of the laser beam energy: 3.84%

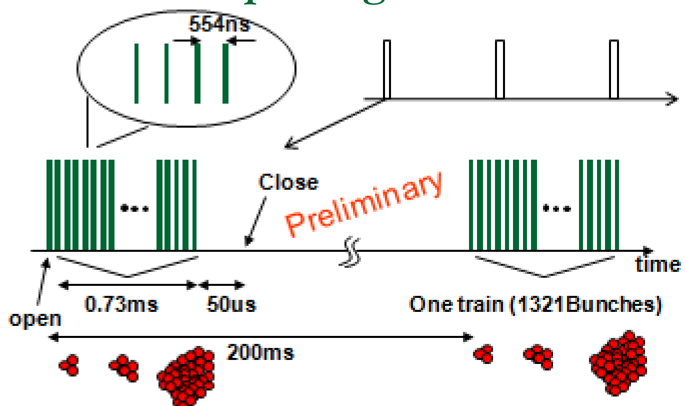


- Duration of measurement time: 20mins
- Average of the energy: 46.53μJ/Φ5mm
- Stability of the laser beam energy: 3.3%

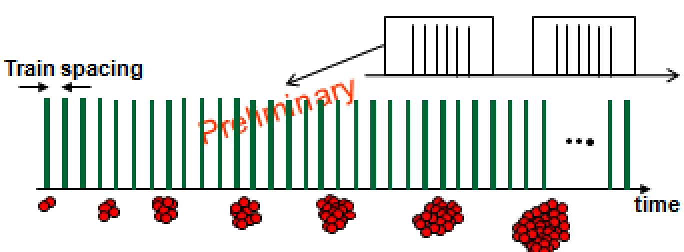


Distortion by UV+Laser

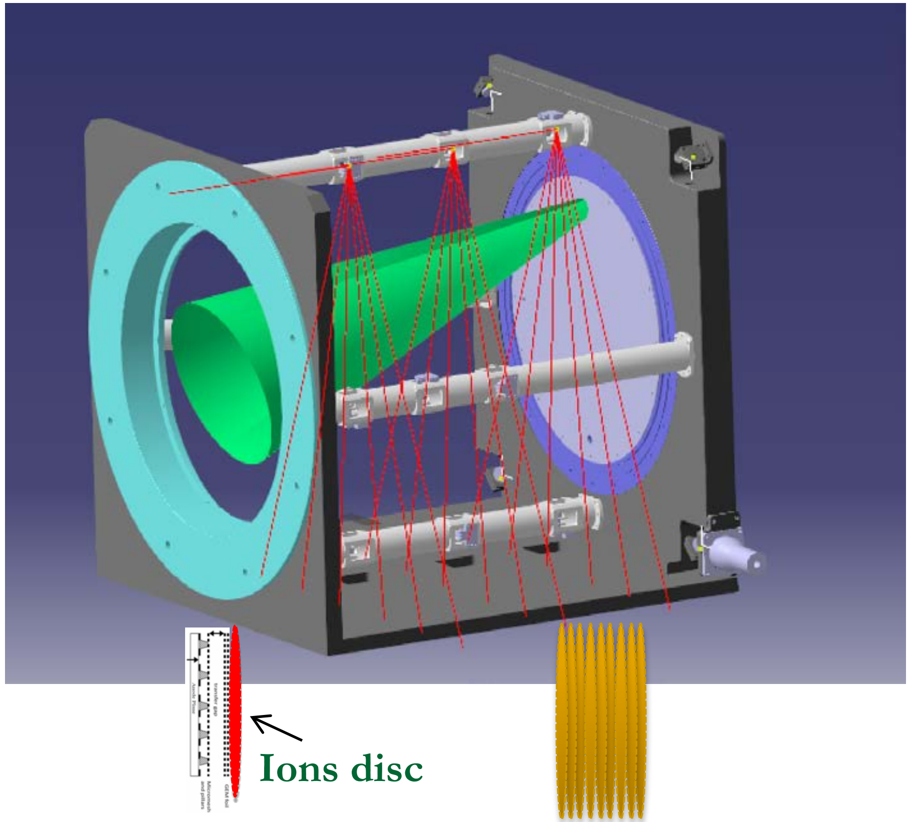
- To mimic the bunch structure & the ions distortion with UV light and laser split beam
- In the case of CEPC-TPC
  - Bunch-train structure of the CEPC
- In the case of ILD-TPC
  - Bunch-train structure of the ILC
  - Power pulsing mode

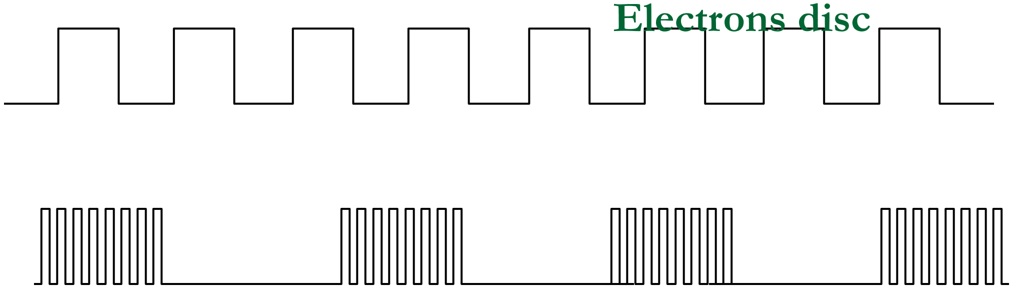


Beam structure of ILC



Beam structure of CEPC





Shutter time similar to ILC and CEPC beam structure

- Low power consumption ASIC FEE chip R&D
    - 65 nm CMOS process
    - 5mW/ch with ADC

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

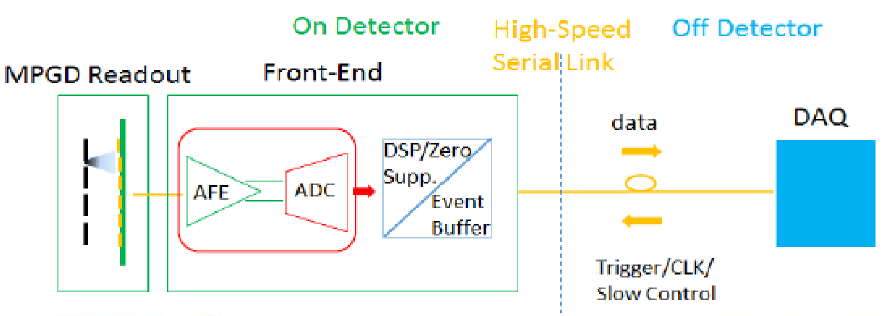
ASIC FEE requirements

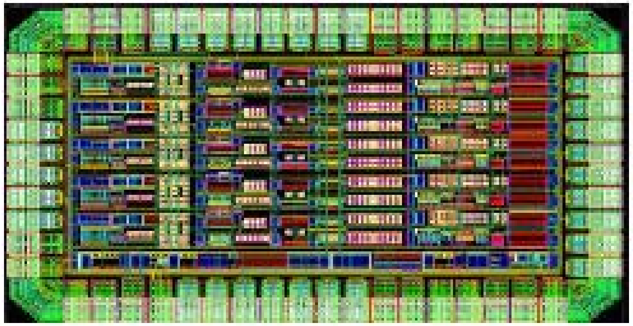
- Requirement for the front-end electronics
  - Analog front-end, including preamplifier and shaper
  - Waveform sampling ADC in 10b and 20-40MSPS
  - Continuous working, no power pulsing ⟶ Low power consumption

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

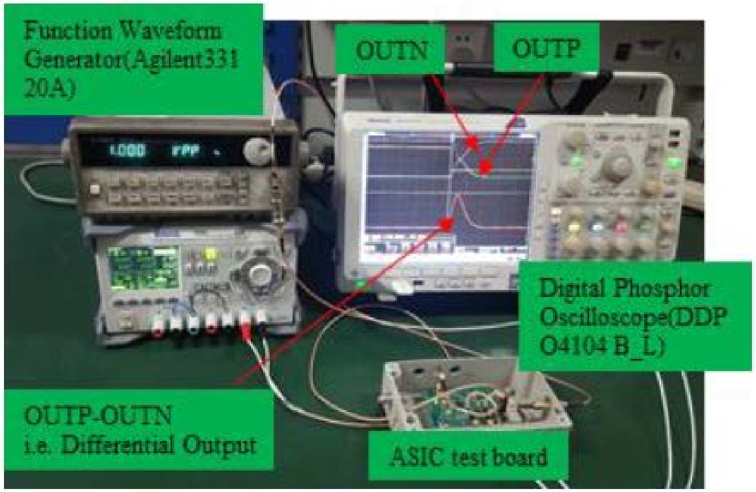
ASIC FEE R&D

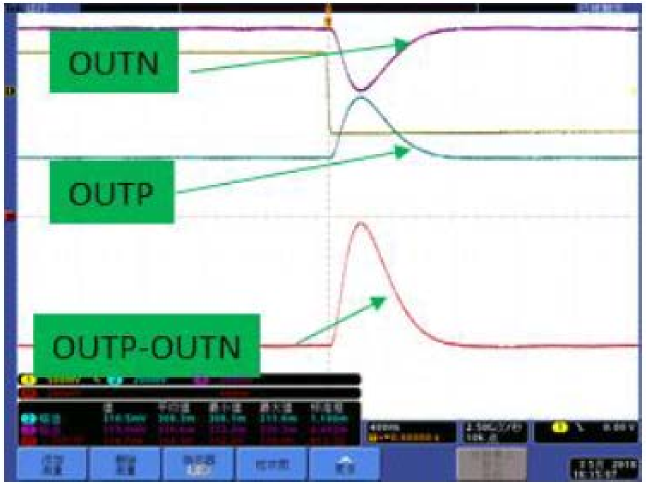
- Develop a low power and highly integration front-end ASIC in 65 nm CMOS
- Each channel consists of the analog front-end (AFE) and a SAR ADC in 10b and up to 40 MSPS
- Less than 5 mW per channel





1320um x 838um





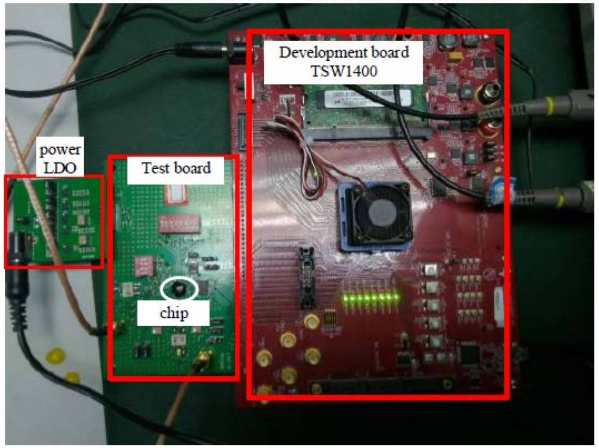
Preliminary of ASIC FEE R&D

- 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



- Test setup
  - TSW1400EVM

Manpower and future plan

- TPC detector module and prototype R&D @IHEP
  - Huirong Qi
  - Haiyun Wang(PhD,IHEP), Zhiyang Yuan(PhD,IHEP), Ling Liu (Master,IHEP)
  - Prof. Ouyang Qun, Prof. Jin Li
  - Funding from MOST and NSFC

- FEE Electronics R&D &Tsinghua
  - Zhi Deng
  - Yiming Cai(PhD,THU), Zhao Mingrui (Master, THU) and three PhDs in electronics lab
  - Prof. Yuanning Gao, Prof. Yulan Li
  - Funding from NSFC

Summary

TPC detector module and prototype R&D

- **No Gating device options used for Higgs/Z pole run**
- **Continuous Ion Back Flow due to the continuous beam structure (Developed in IHEP)**
- **Preliminary results: Key factor of IBF×Gain=5**
- **Low discharge and spark possibility**
- **TPC prototype with the laser calibration sytem**

Low power front-end ASICs have been developed to meet the stringent requirements of CEPC TPC readout by

- **Using advanced 65 nm CMOS process**
- **Adopting circuit structure with minimized analog circuits such CR-RC shaper and SAR ADC**

Thanks.