Time Projection Chamber tracker detector

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Outline

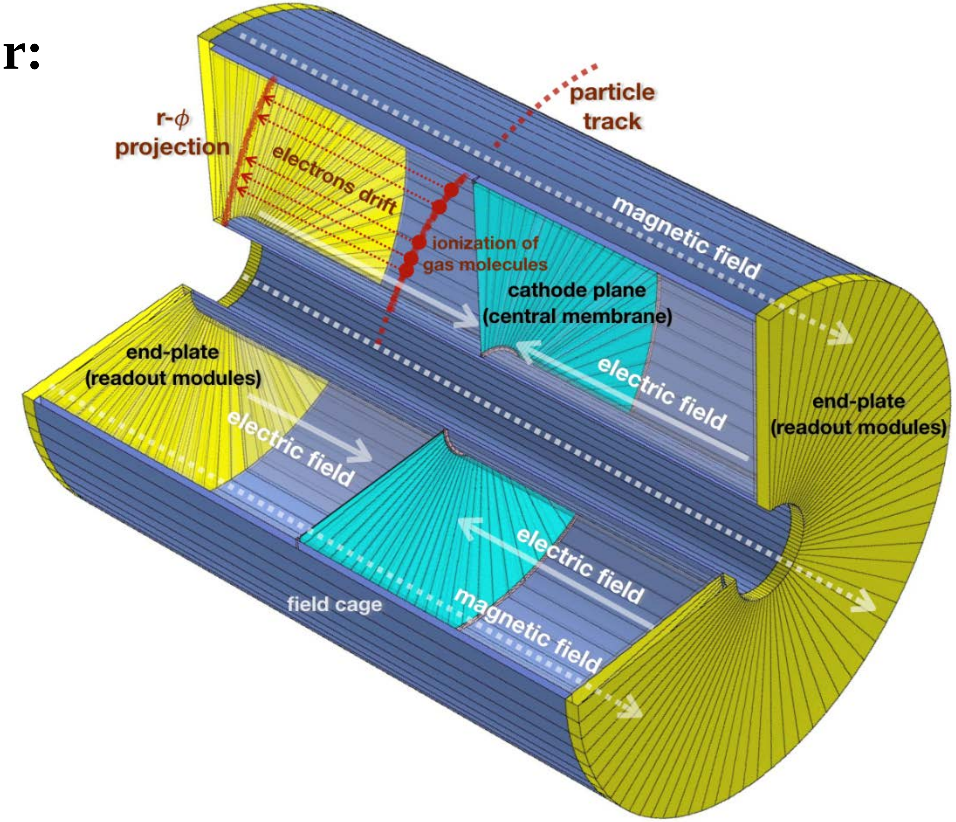
- Requirements and challenges
- Baseline design
- Feasibility study of TPC detector
- R&D activities
- Summary

TPC detector for 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.

TPC detector as the tracker detector:

- **Motivated by the H tagging and Z**
- **High magnetic field**
- **Full 3-D track reconstruction**
- **Higher accuracy < 100μm(Overall along the drift)**
- **Precise dE/dx**
- **Better two track resolution**
- **Easily assembled using the modules**
- **Minimal material budget**
- **Drift time gives the longitudinal coordinate**
- **MPGDs as the readout**

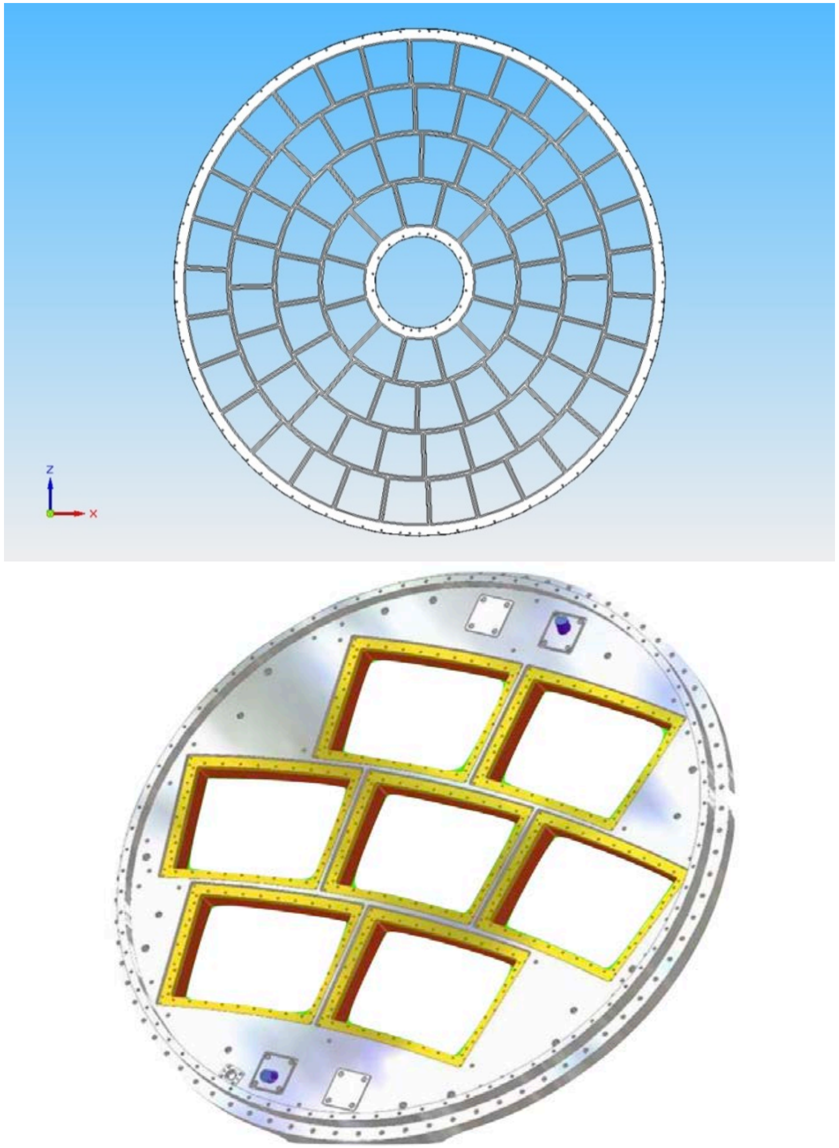


Overview of TPC detector concept

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
  - <1X0 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

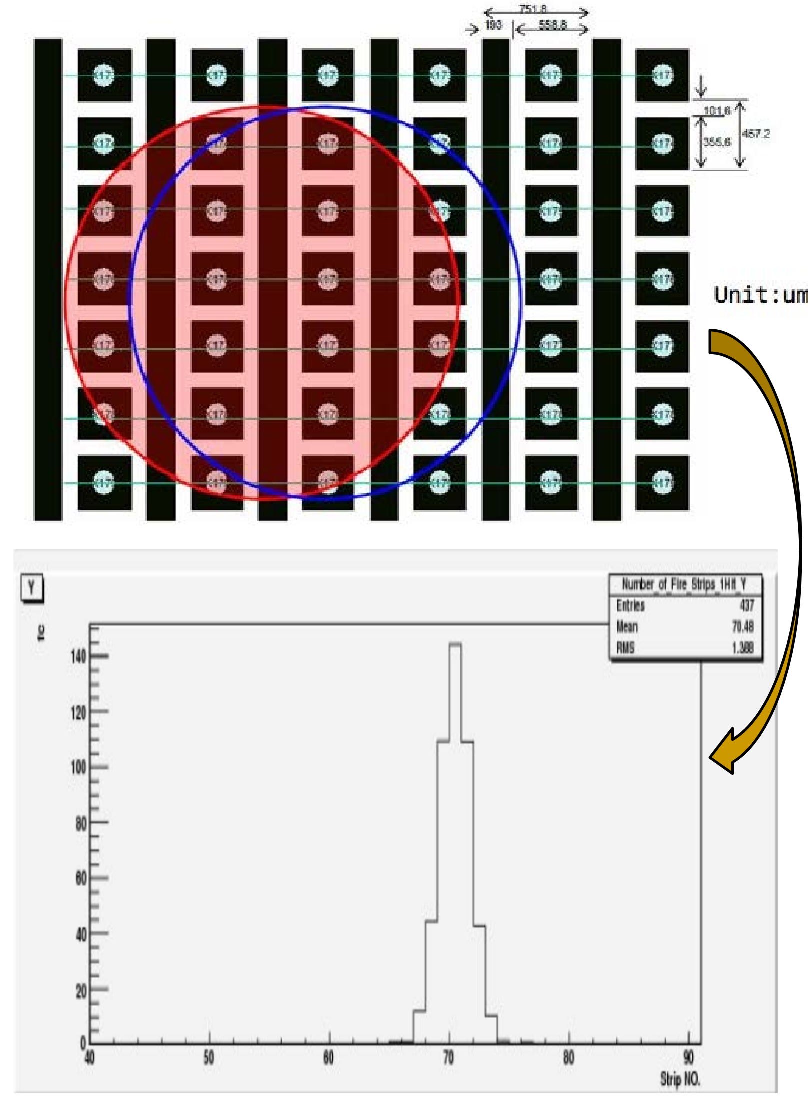


TPC detector endplate concept

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

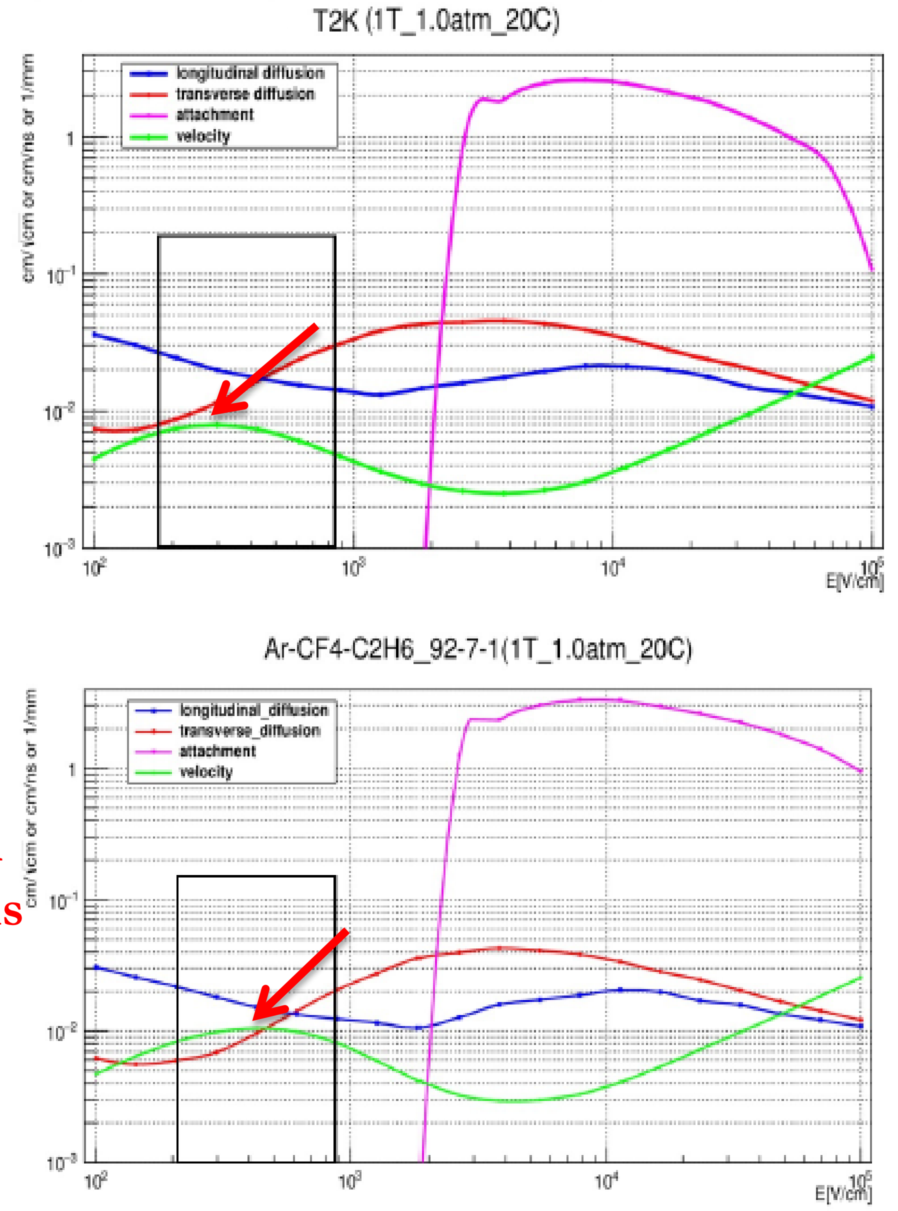
Operation mixture gases

Gas for the micro pattern detector:

- **Drift velocity (green line)**
- **Transverse diffusion coefficient (red)**
- **Longitudinal diffusion coefficient (blue)**
- **Attachment coefficient (purple) as a function of the electric field**
- **The possible operation range (black rectangle)**

Due to the long drift distance of 3.0m, A mixture gases with a large drift velocity is also chosen in experiments.

$Ar/CF_4/C_2H_6$ saturated drift velocity is roughly 20% higher than the default gas mixture(T2K) and the diffusion coefficients are lower.

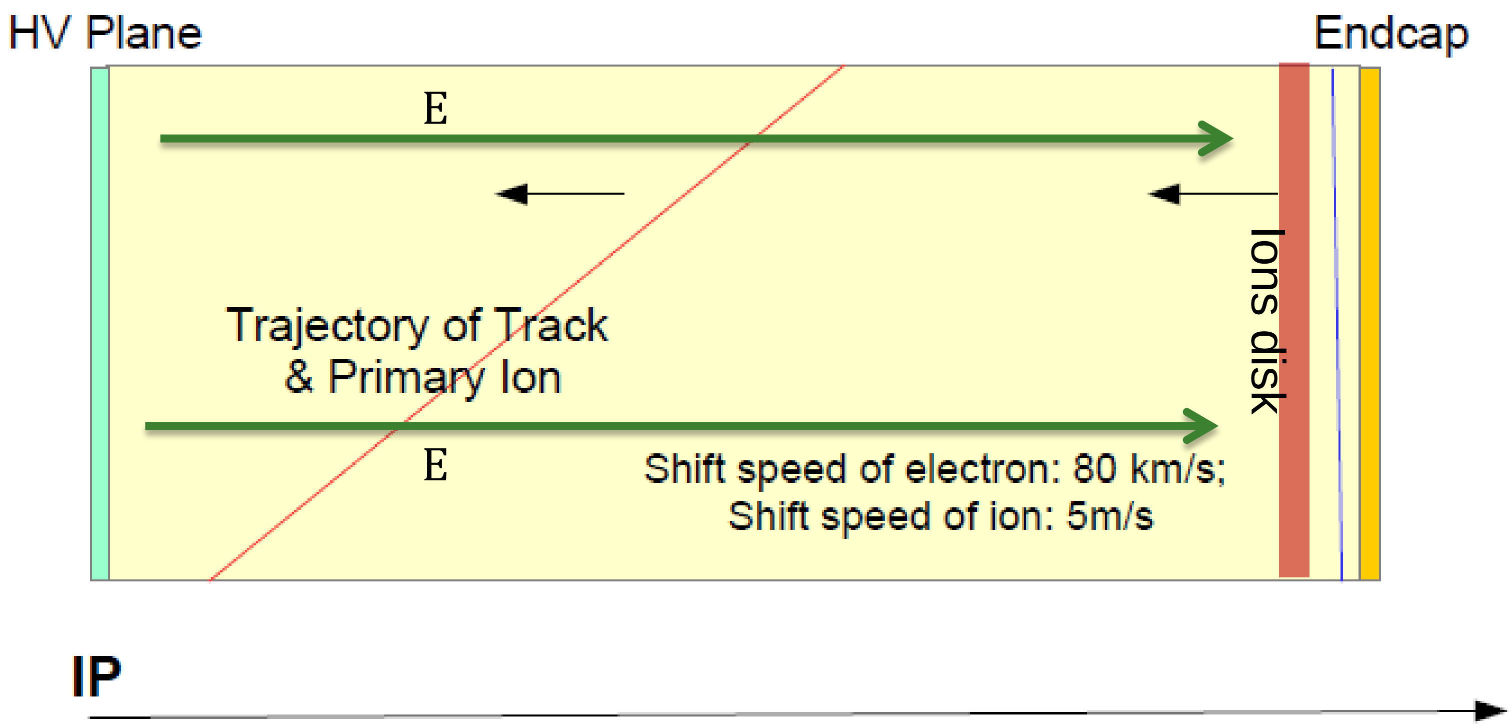


Drift velocity study of gas mixtures

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} • V_{drift}



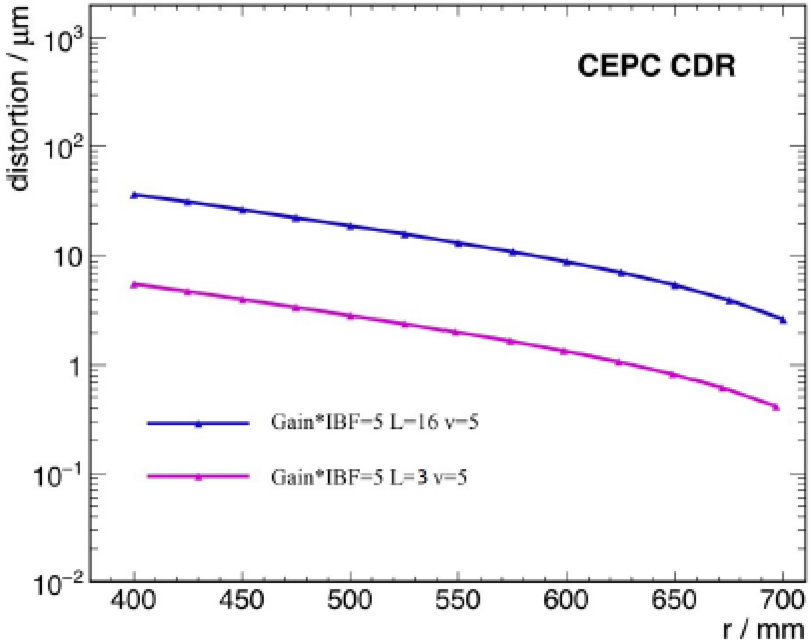
Total ions in chamber: ~ Back flow ions ~(1 + k), k = Gain×IBF + Primary

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



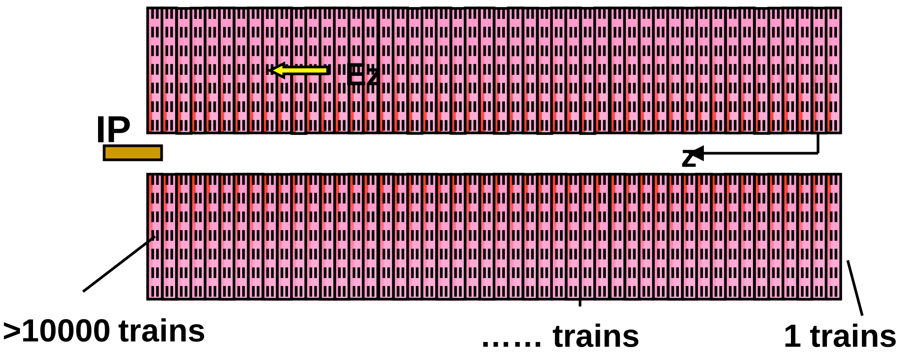
Distortion on the hit position reconstruction

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 :

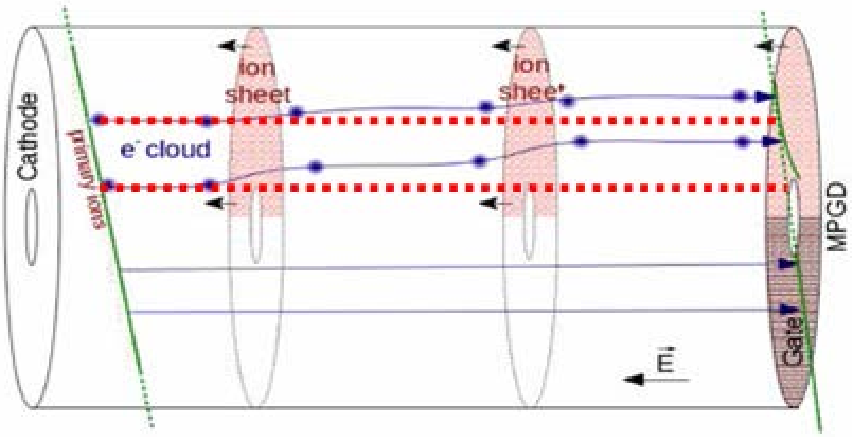
- ~100 μm position resolution in rφ
- Distortions by the primary ions at CEPC are negligible
- More than 10000 discs co-exist and distorted the path of the seed electrons
- The ions have to be cleared during the ~us period continuously
- Continuous device for the ions
- Long working time



Amplification ions from the endplate @CEPC

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

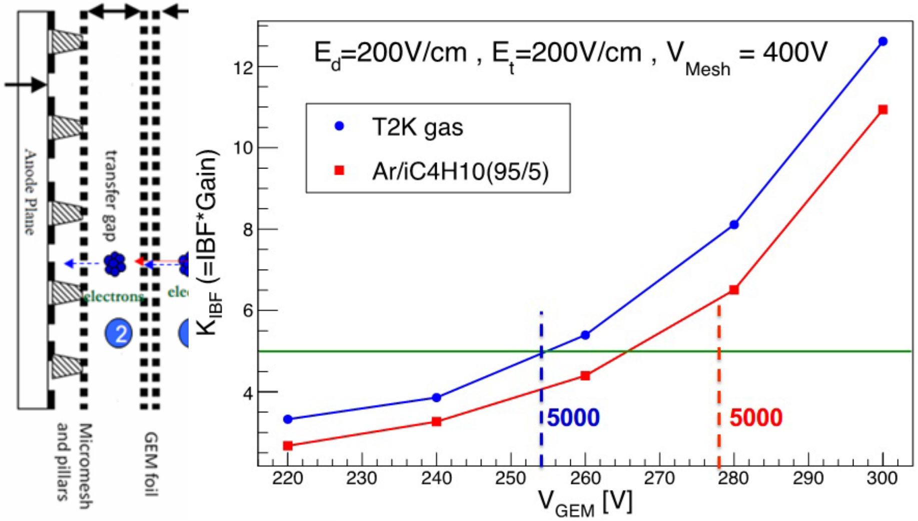


Ions backflow in drift volume for distortion

Feasibility study of TPC detector

Continuous IBF module:

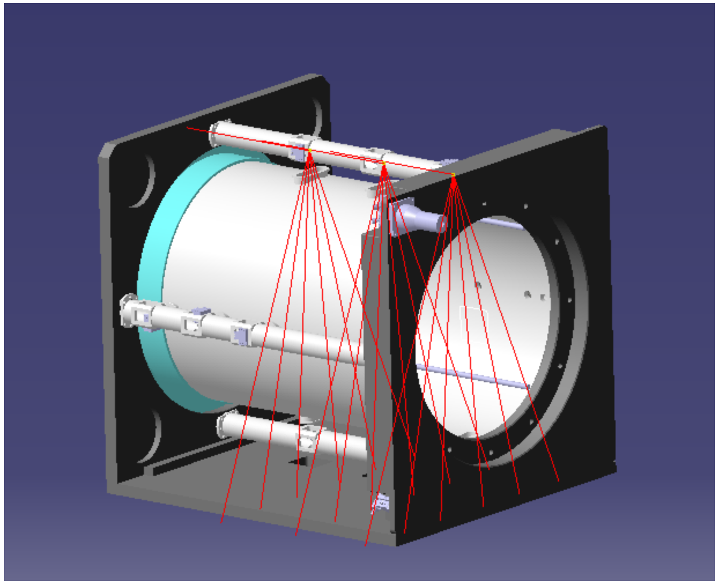
- Operation at Higgs and Z-pole run
- Continuous Ion Back Flow due to the continuous beam structure
- Low discharge and spark possibility
- Space charge effect for IBF
- Gain: 5000-6000
- Good energy resolution: <20%



Continuous IBF prototype and IBF × Gain

Laser calibration system:

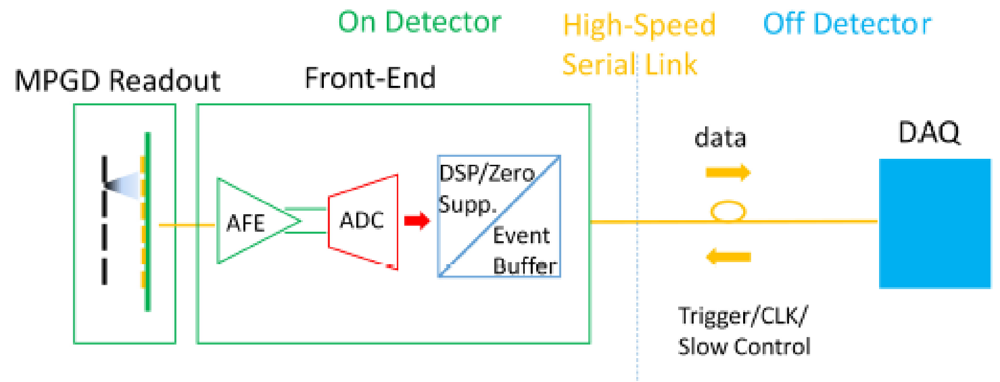
- The ionization in the gas volume along the laser path occurs via two photon absorption by organic impurities (Nd:YAG laser @266nm)
- Laser calibration system around the chamber
- Calibration of the drift velocity, gain uniformity, the distortion
- High stability of the laser beam (<5μm)



TPC prototype integrated with laser system

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

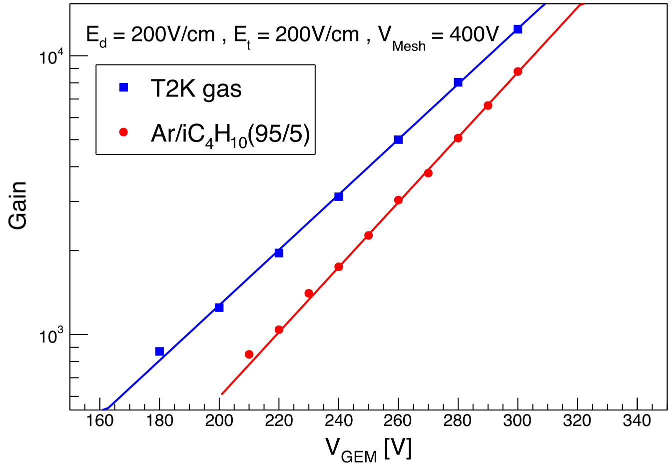
Total number of channels		1 million per endcap
AFE (Analog Front-End)	ENC (Equivalent Noise Charge)	500e @ 10pF input capacitance
	Gain	10 mV/fC
	Shaper	CR-RC
	Peaking time	100 ns
ADC	Sampling rate	$\geq$ 20 MSPS
	Resolution	10 bit
Power consumption		$\leq$ 5 mW per channel
Output data bandwidth		300–500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

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

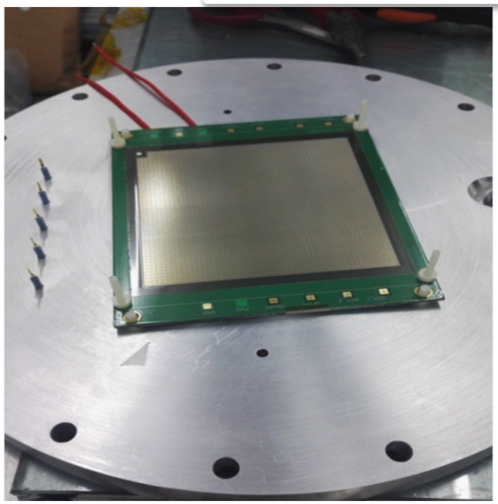
TPC detector module@ IHEP

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

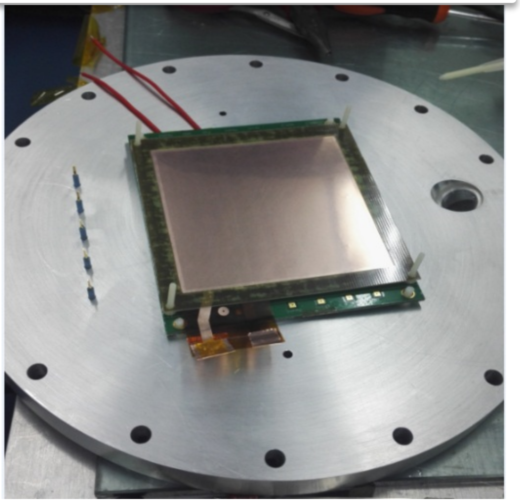
- Test with GEM-MM module
  - New assembled module
  - Active area: 100mm×100mm
  - X-tube ray and 55Fe source
  - Bulk-Micromegas from Saclay
  - Standard GEM from CERN
  - Avalanche gap of MM:128μm
  - Transfer gap: 2mm
  - Drift length:2mm~200mm
  - Mesh: 400LPI



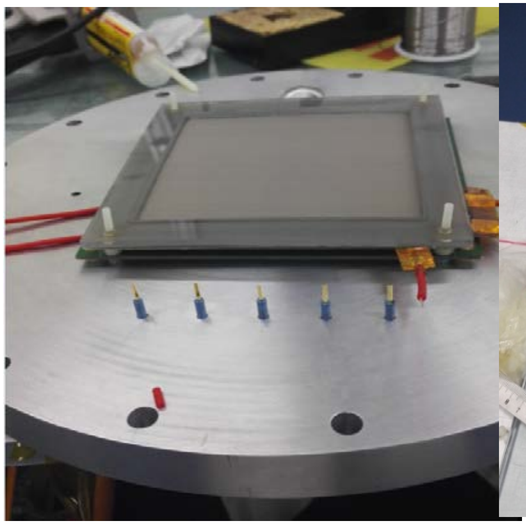
Gain of the detector



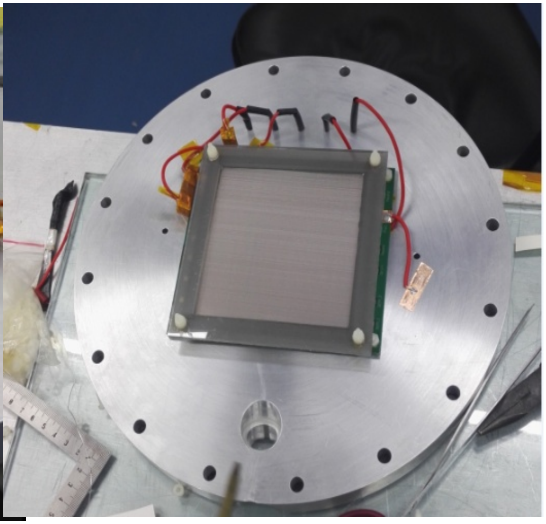
Micromegas(Saclay)



GEM(CERN)



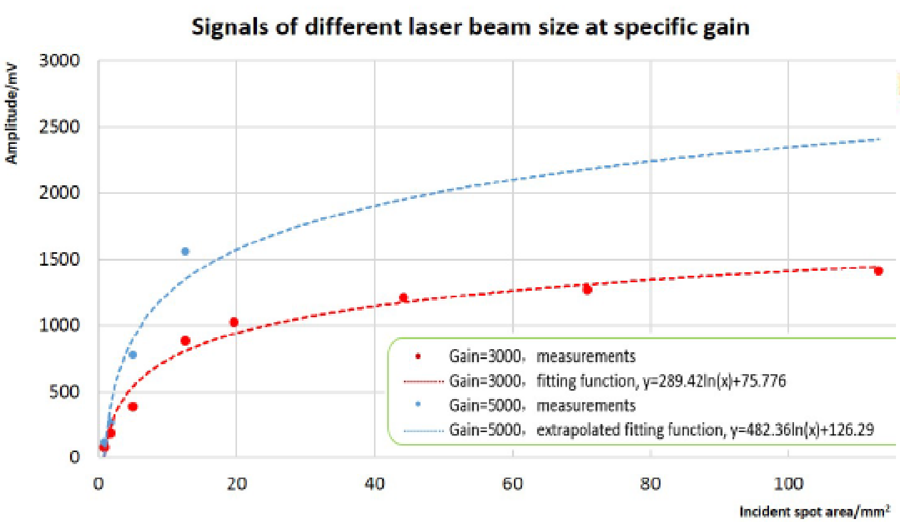
Cathode with mesh



GEM-MM Detector

TPC prototype@ IHEP/Tsinghua

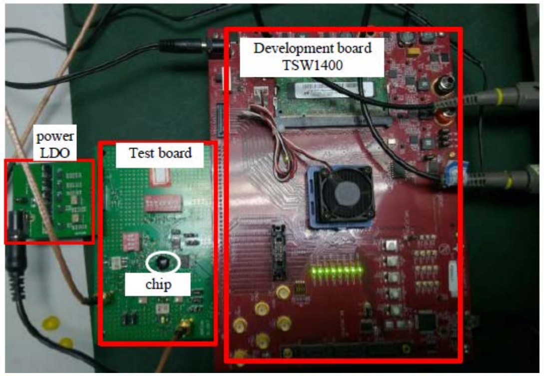
- Study and estimation of the distortion from the IBF and primary ions with the laser calibration system
- Main parameters
  - Drift length: ~510mm, Readout active area: 200mm×200mm
  - Integrated the laser calibration with 266nm
  - GEMs/Micromegas as the readout
  - Matched to assembled in the 1.0T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

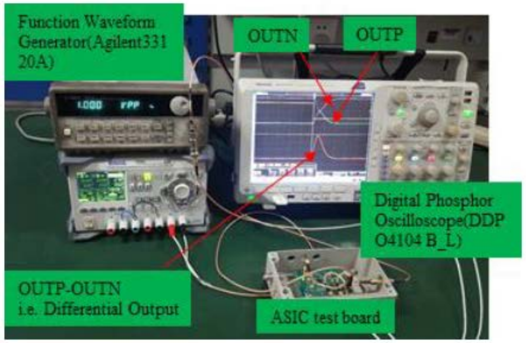


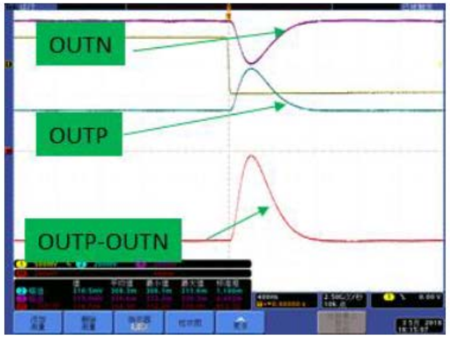
TPC prototype with the laser calibration system

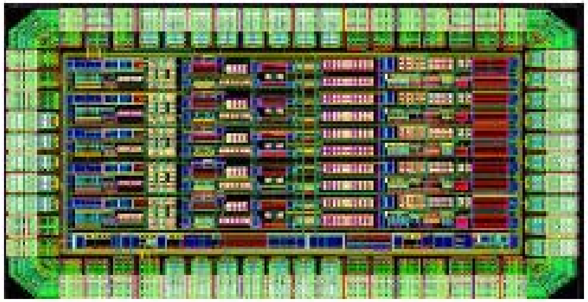
ASIC FEE R&D @Tsinghua

- 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

The Time Projection Chamber presented here provides an good starting point for TPC research and development in the context of the CEPC beam environment.

Several critical challenge issues have been identified in pre-studies

- **TPC is promising for the CEPC (e+e- collider with High event rate Z pole operation**
- **Validation of the preliminary results from the combination GEM+Micromegas detector module: (IBF×Gain=5)**
- **TPC prototype with the laser calibration system developed**
- **Low power front-end ASICs have been developed using advanced 65 nm CMOS process**

Collaboration with international teams (LCTPC collaboration group, Japan-KEK group, France-Saclay group)

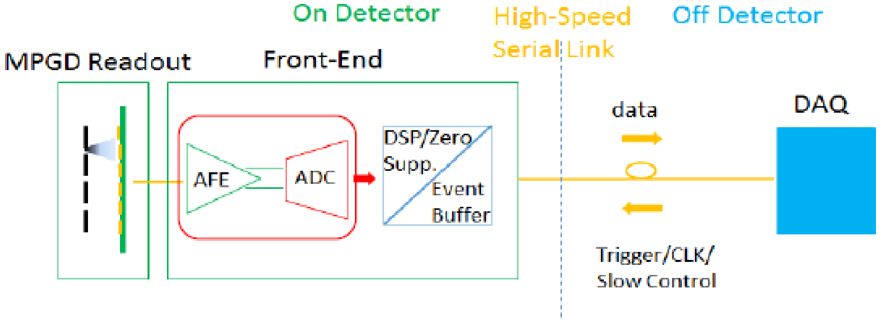
Going to TDR for next step

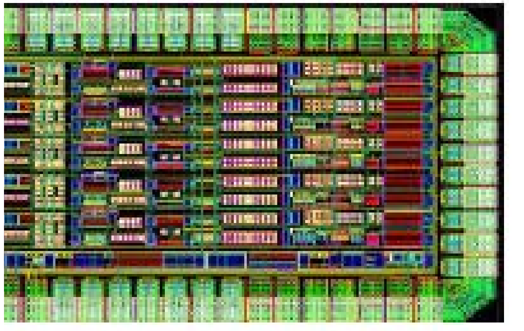
Thanks.

Backup

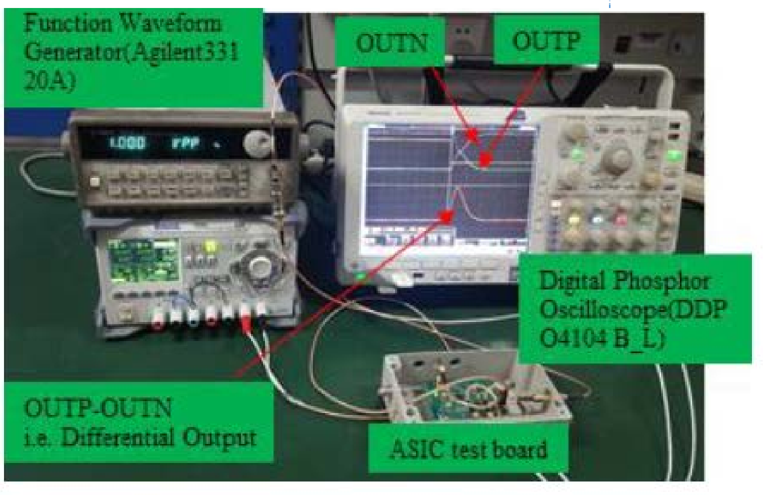
ASIC FEE R&D

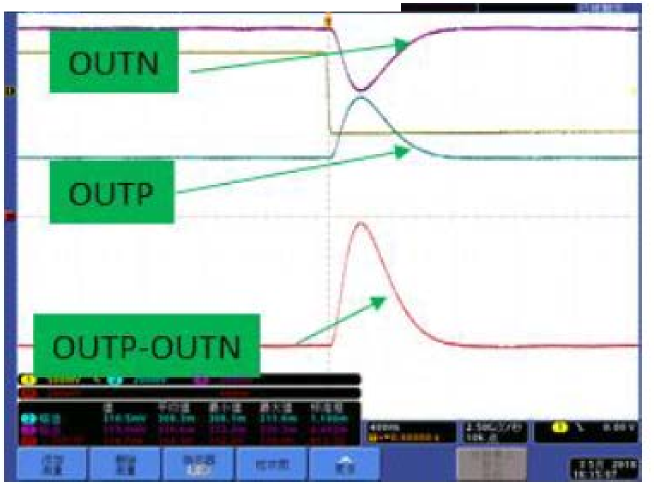
- Develop a low power and highly integration front-end ASIC in 65 nm CMOS
- Each channel consists of the analog front-end (AFE) and a SAR ADC in 10b and up to 40 MSPS
- Less than 5 mW per channel





1320um x 838um



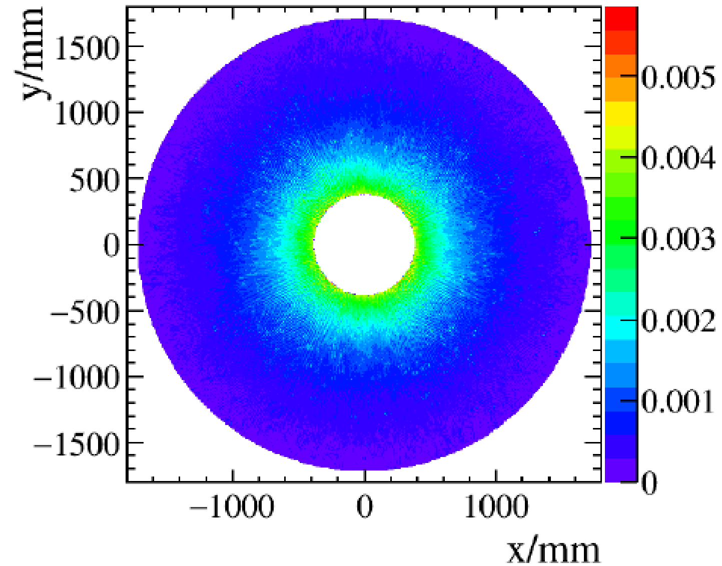


High rate at Z pole

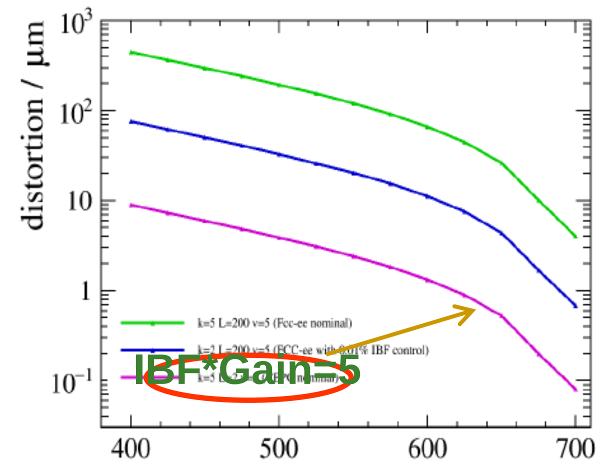
ArXiv: 1704.04401
Mingrui, Manqi, Huirong

- 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 $\times 10^{14}$ number of voxels/s @DAQ/40MHz
  - Average voxel occupancy: 1.33 $\times 10^{-8}$
  - Voxel occupancy at TPC inner most layer: ~2 $\times 10^{-7}$
  - Voxel occupancy at TPC inner inner most layer : ~2 $\times 10^{-5}$ @FCCee benchmark luminosity

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



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



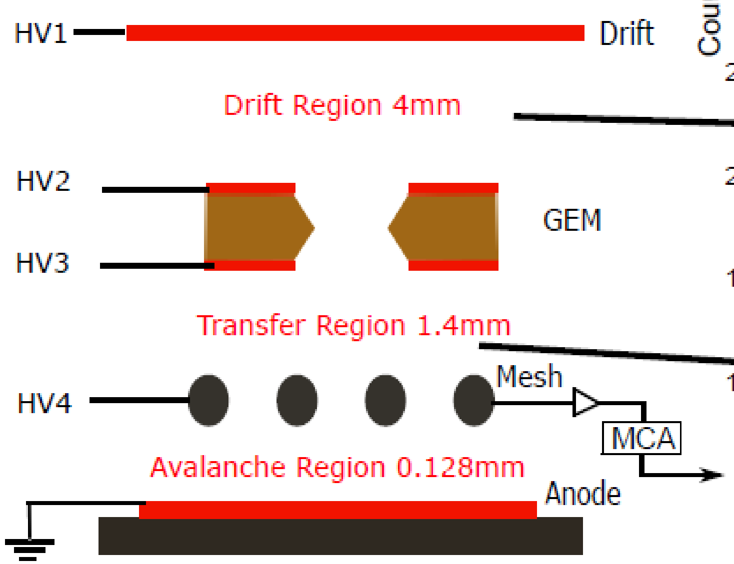
Distortion of as a function of electron initial r position

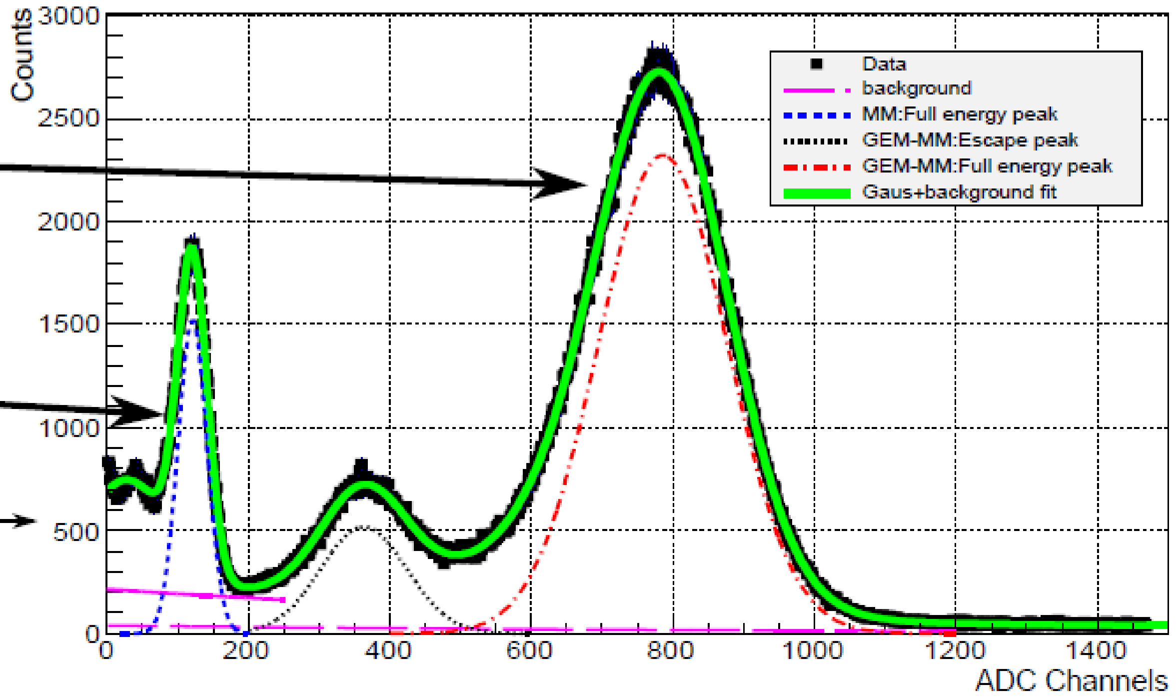
- Ions backflow reduced
- TPC detector module R&D
  - Combination detector
  - Discharge for IBF

GEM+MM@CEPC R&D

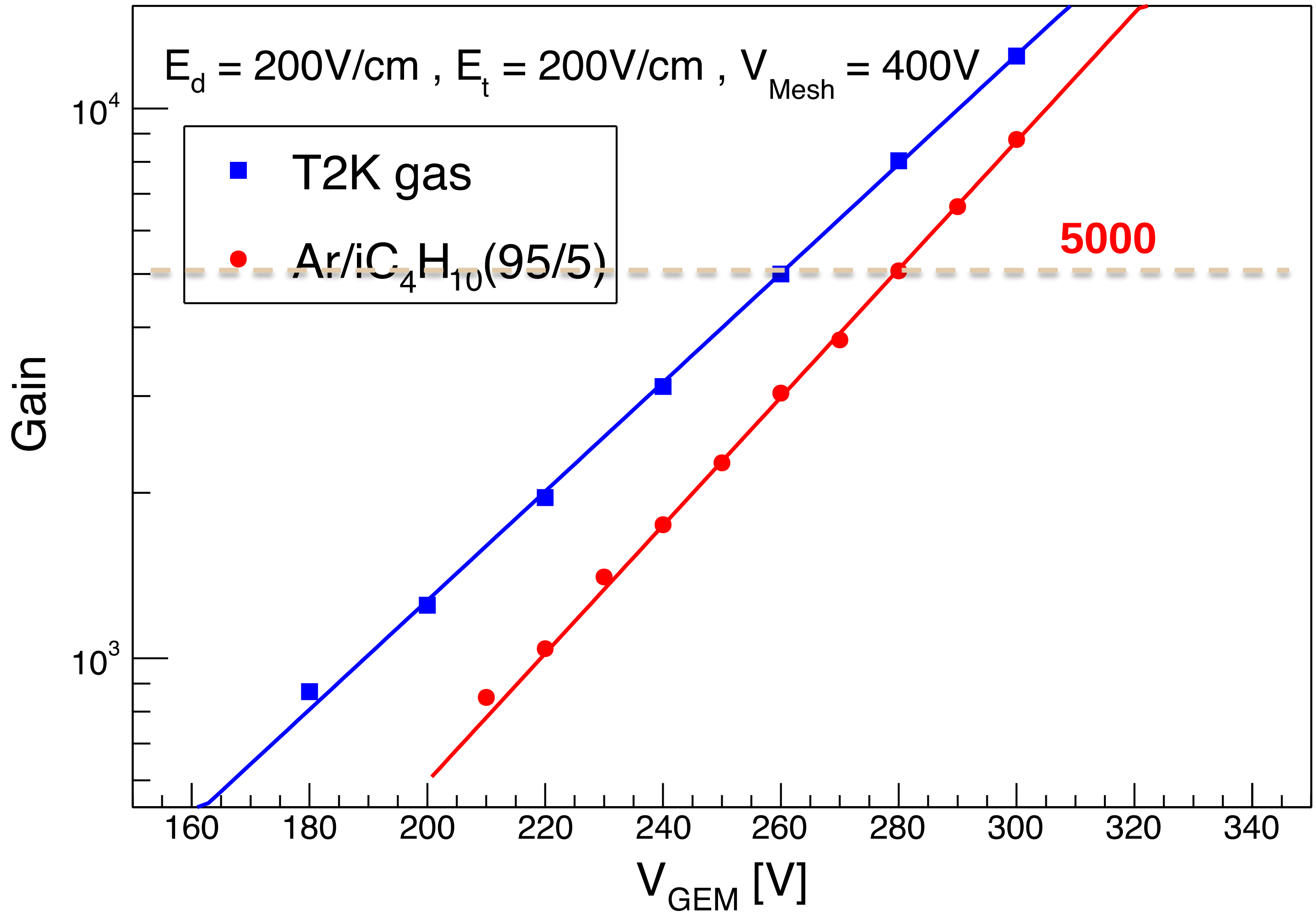
e+e- machine
Primary N_{eff} is small: ~30
Pad size:1mm×6mm

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

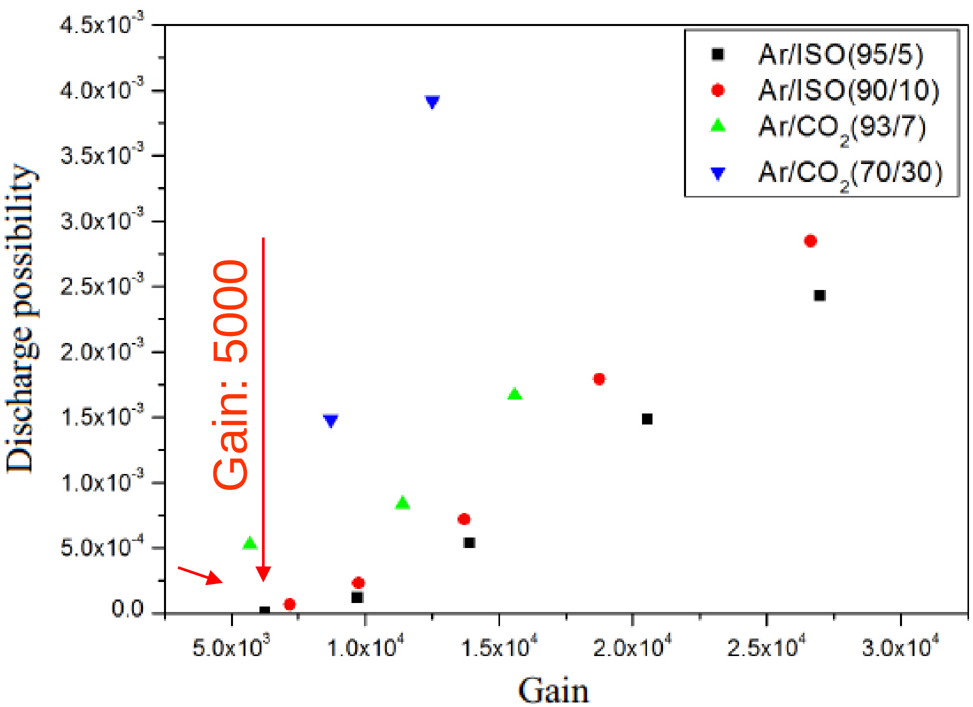


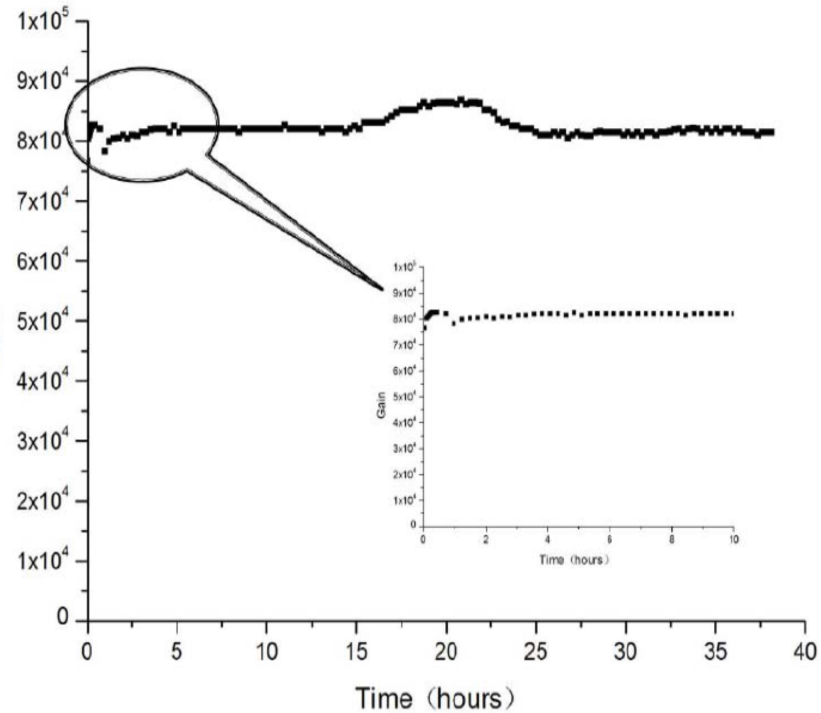


Gain of the hybrid structure detector



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

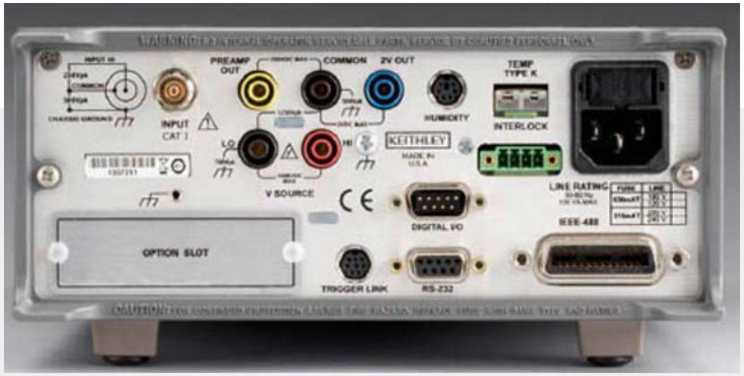
Electrometer/High Resistance Meter

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

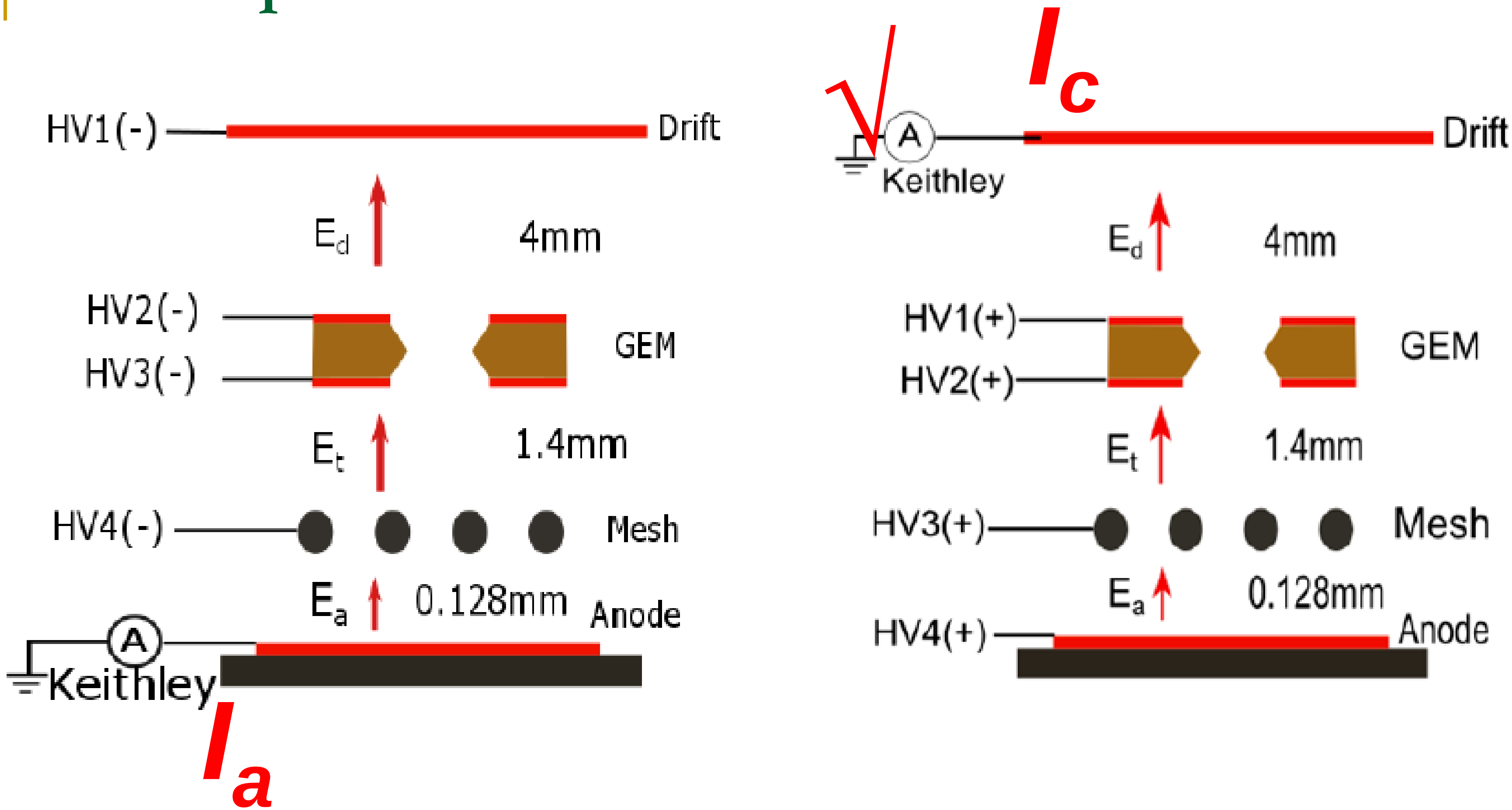
Measuremnt of GEM-MM module

- 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

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

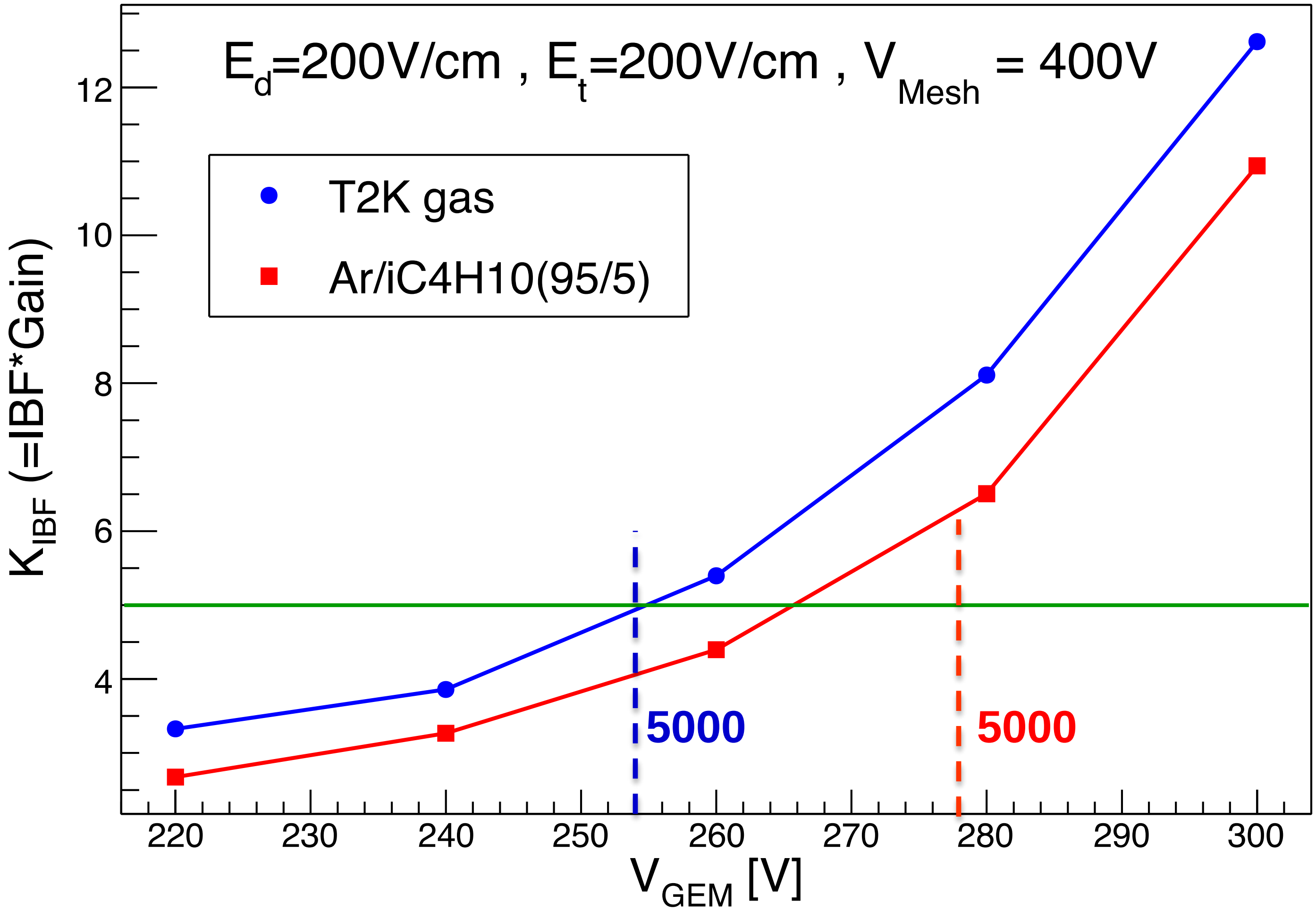
Two steps



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

Key IBF factor: IBF × Gain

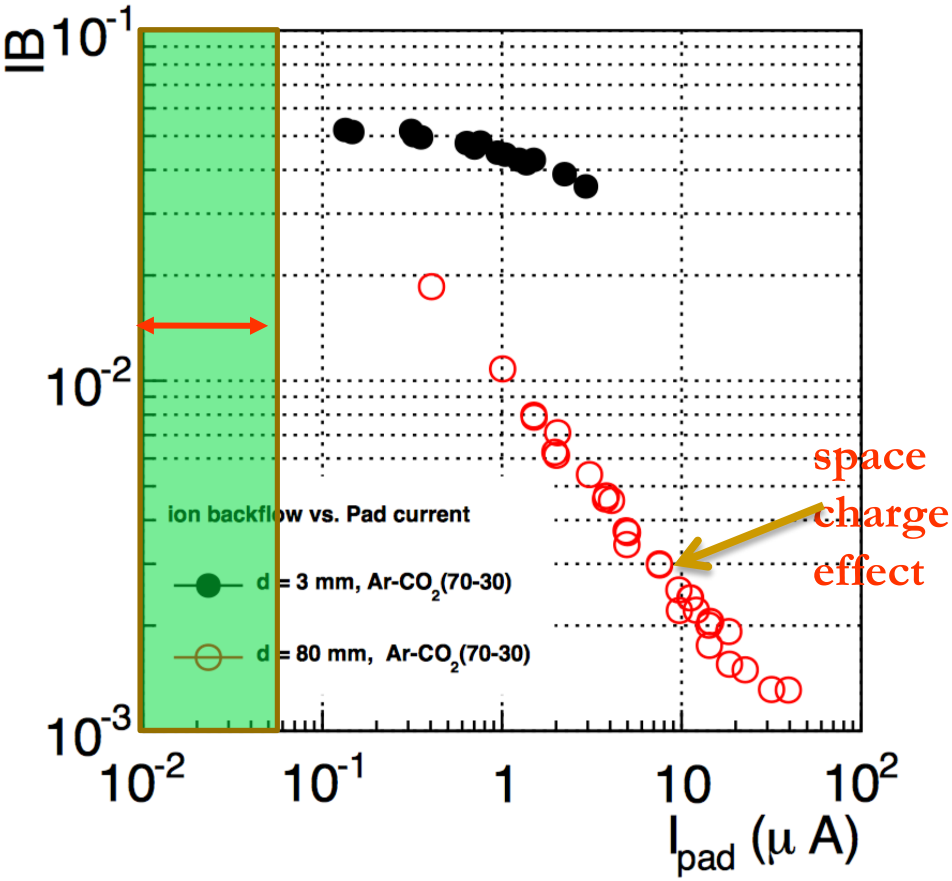
Preliminary results in 2018

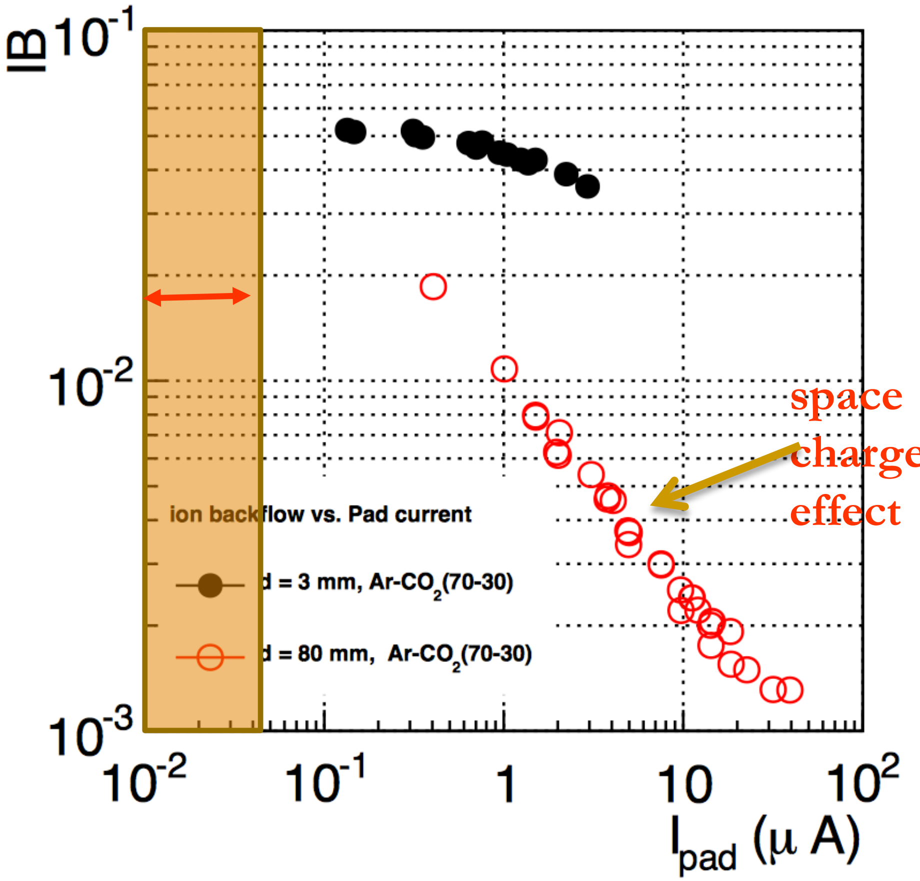


- Space charge effect for IBF

Check and answer- I_{pad}

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

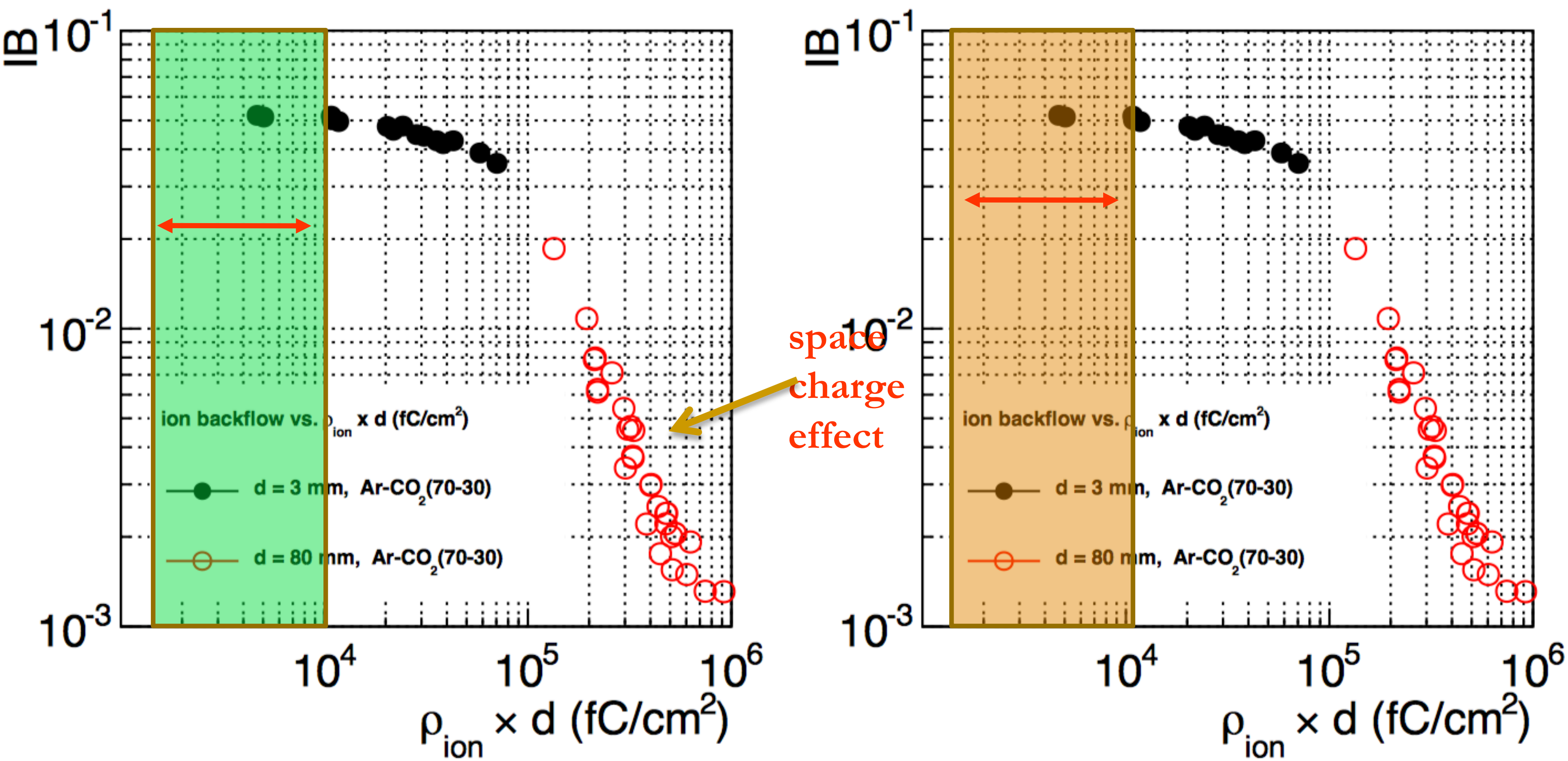




Green， T2K， Et=200V/cm, Ed=200V/cm, V_mesh=400V, V_Gem:30~300V
Yellow， Ar/iso(95/5) ， Et=200V/cm, Ed=200V/cm, V_mesh=400V, V_Gem:30~300V

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

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



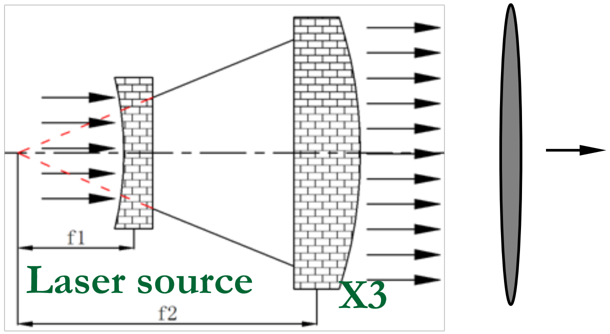
Green: T2K，Yellow: Ar/iso(95/5)

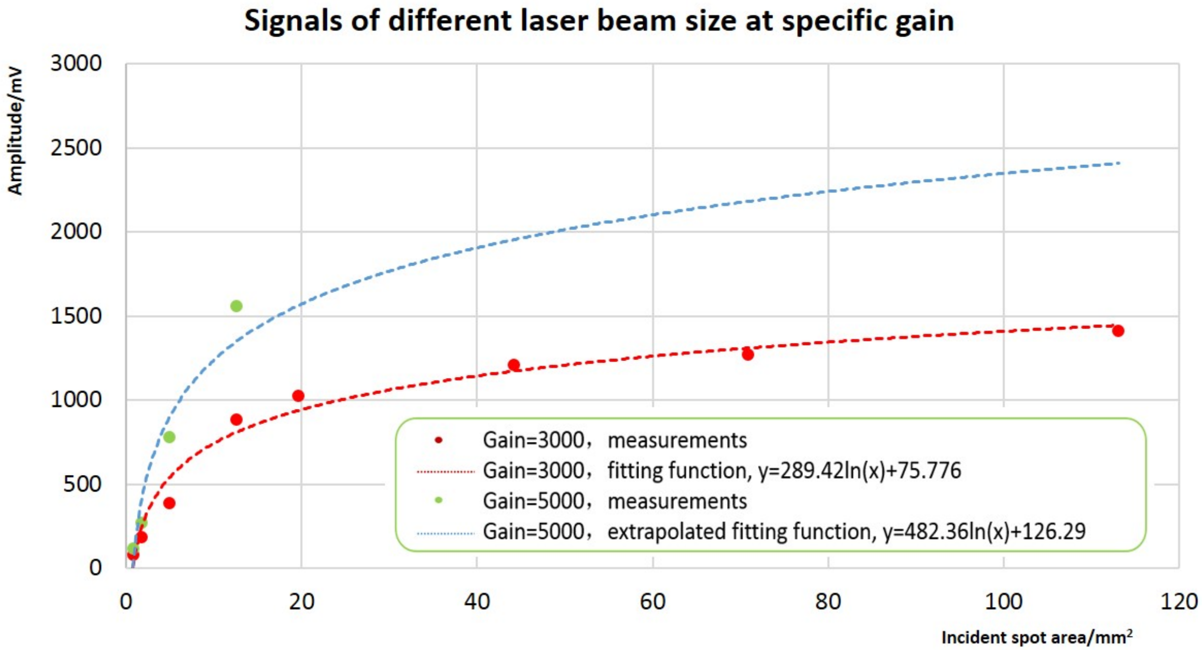
T2Kgas Ic: 4pA～59pA，～10^3 （fC/cm^2）
Ar/iso gas Ic : 3.5pA~53pA, ～10^3 （fC/cm^2）

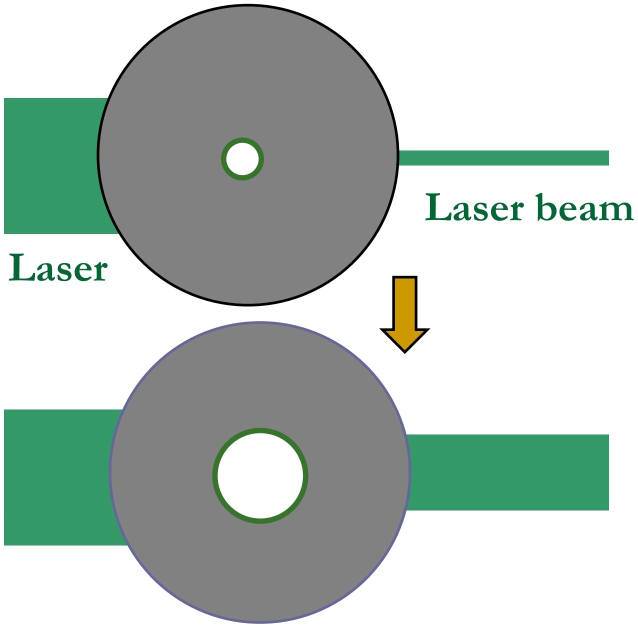
- Calibration (Drift velocity/Uniformity/Distortion)
- TPC detector prototype R&D
  - Signal of the 266nm laser beam @MPGD
  - Stability of the position@100um resolution
  - Stability of the energy @ASIC FEE

Collimator for the laser beam@Φ1~ Φ 12mm

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





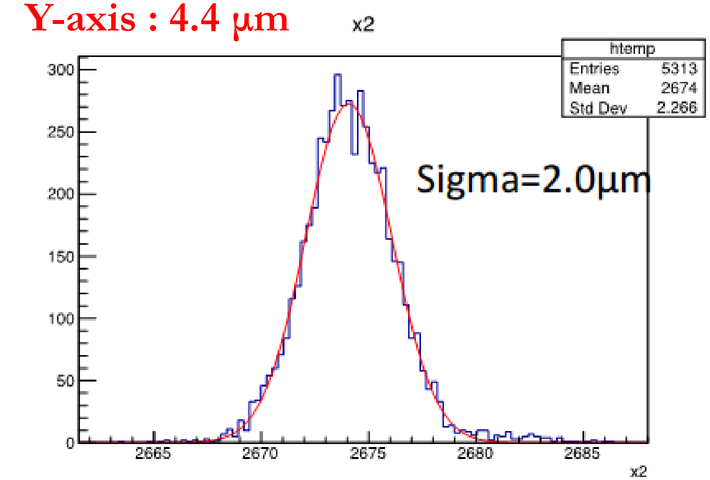


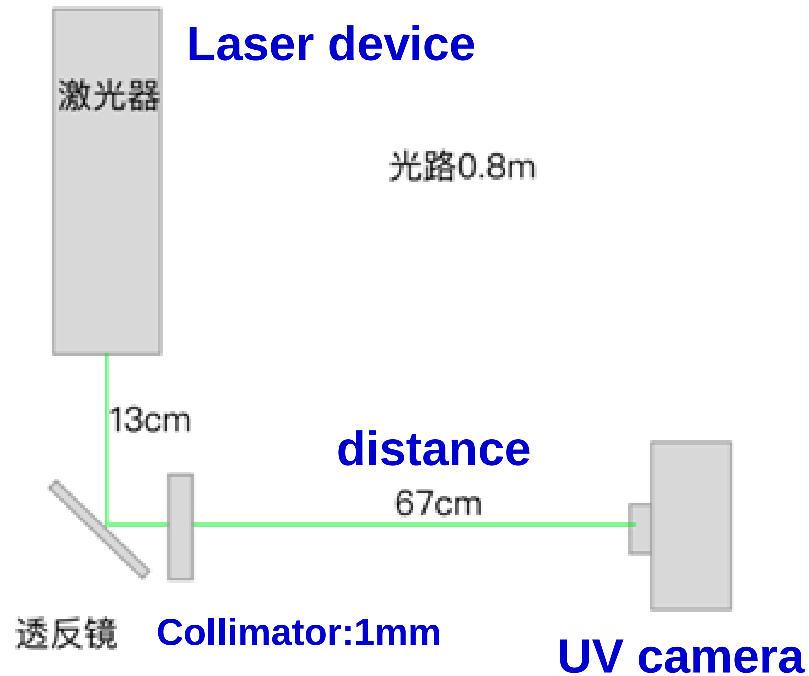
Area of laser beam in detector

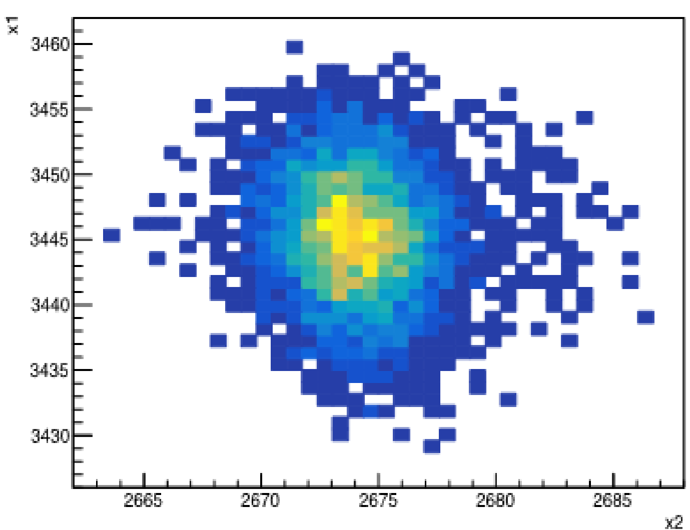
Stability of the laser beam position

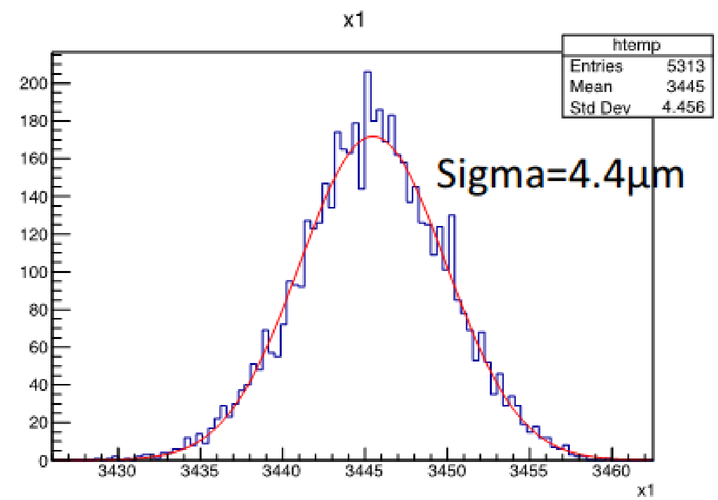
GOOD !

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



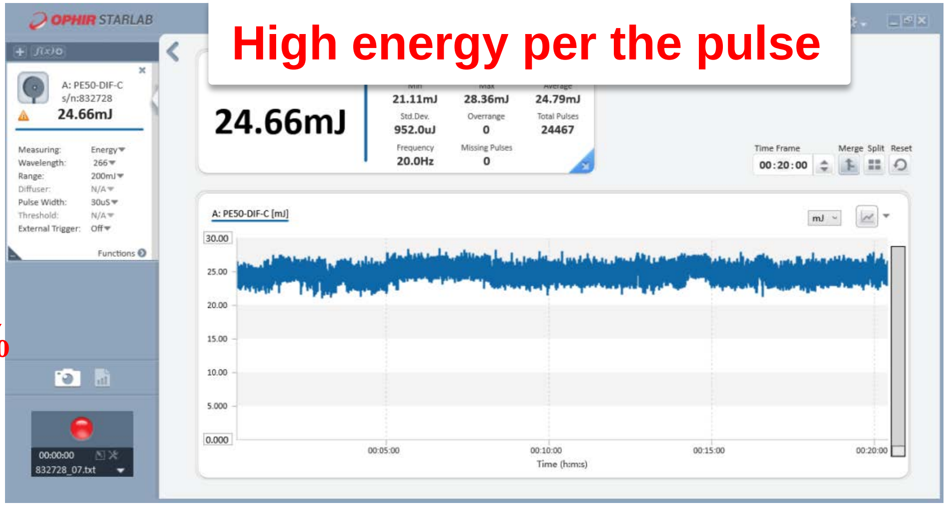




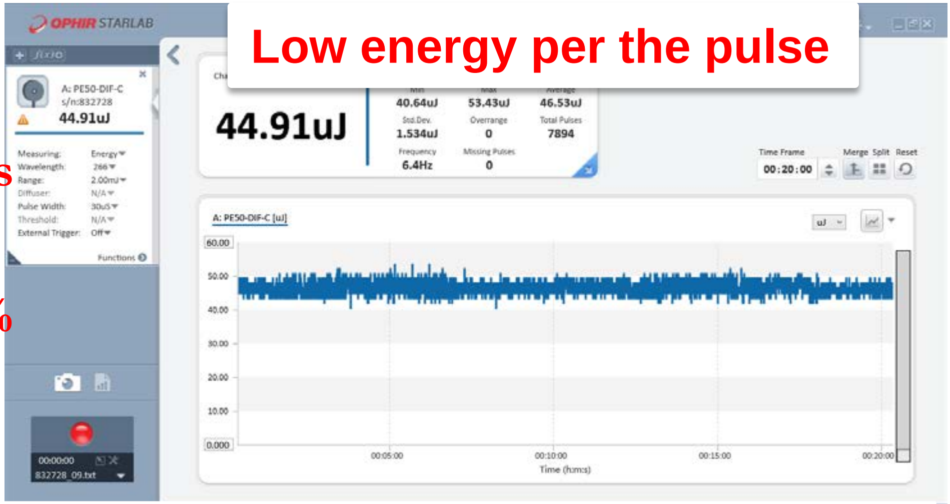


Stability of the laser beam energy

GOOD !



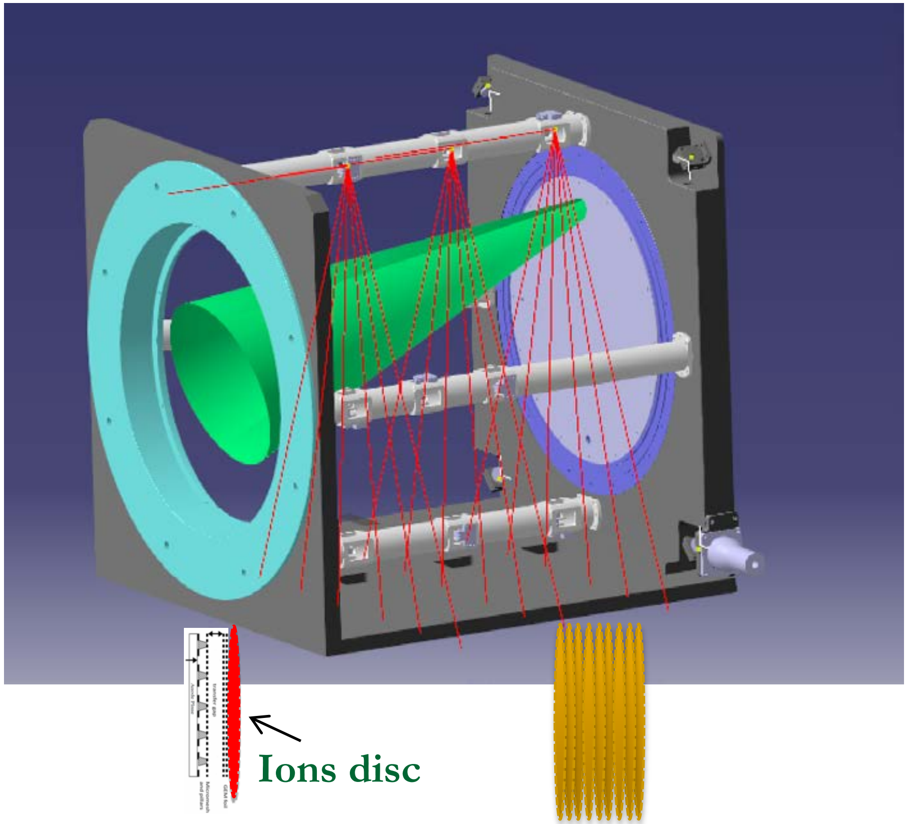
- Duration of measurement time: 20mins
- Average of the energy: 24.79mJ/Φ5mm
- Stability of the laser beam energy: 3.84%

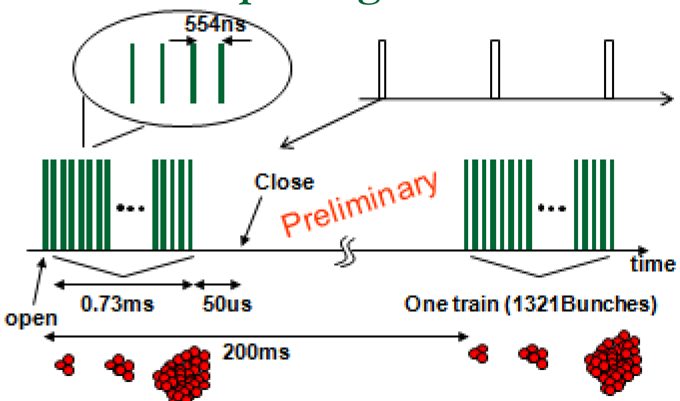


- Duration of measurement time: 20mins
- Average of the energy: 46.53μJ/Φ5mm
- Stability of the laser beam energy: 3.3%

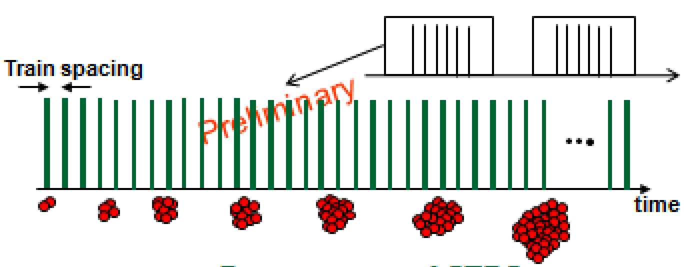
Distortion by UV+Laser

- 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

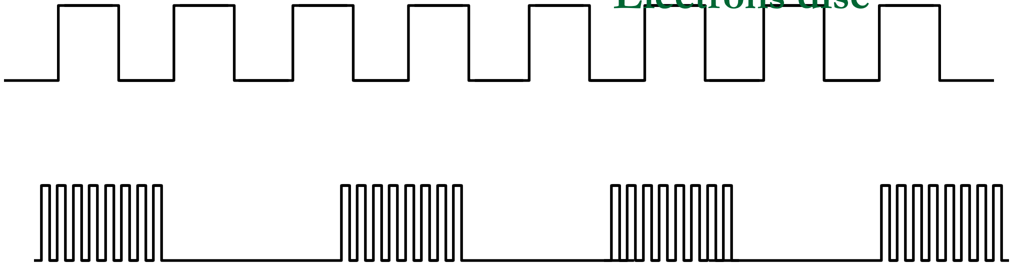


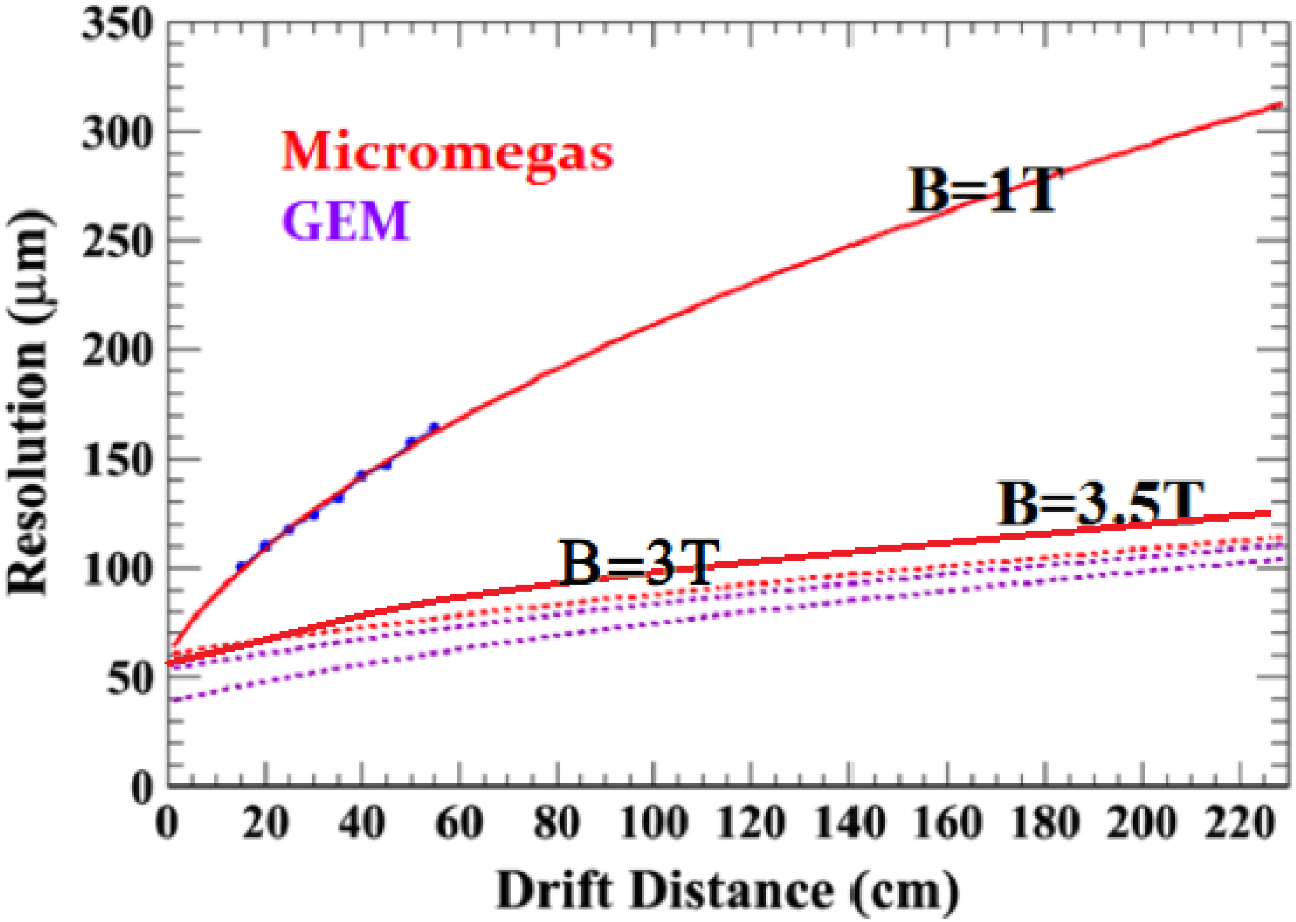


Beam structure of ILC



Beam structure of CEPC


Shutter time similar to ILC and CEPC beam structure



Micromegas 3x7mm^2 pads and GEM 1x6mm^2 pads