Status and prospects of TPC module and prototype R&D for CEPC

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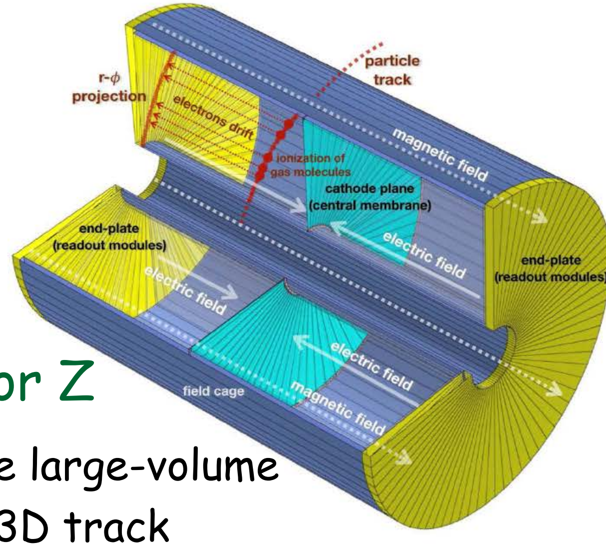
Outline

- Motivation
- TPC module R&D
- TPC prototype R&D
- FEE ASIC R&D
- Summary

Motivation



Momentum resolution (B=3.5T)	$\delta(1/p_t) \approx 10^{-4}/GeV/c$
δ_{point} in $r\Phi$	<100 μm
δ_{point} in rz	0.4-1.4 mm
Inner radius	329 mm
Outer radius	1800 mm
Drift length	2350 mm
TPC material budget	$\approx 0.05X_0$ incl. field cage $< 0.25X_0$ for readout endcap
Pad pitch/no. padrows	≈ 1 mm × (4~10mm) /≈ 200
2-hit resolution	≈ 2 mm
Efficiency	>97% for TPC only ($p_t > 1GeV$) >99% all tracking ($p_t > 1GeV$)

TPC critical R&D for Z

- TPC can provide large-volume high-precision 3D track measurement with stringent material budget
- In order to achieve the high spatial resolution (<100um in all drift length), small pads (e.g.1mmx6mm) are needed, resulting ~1million channels of readout electronics
- Need low power consumption readout electronics working at continuous mode
- Need effectively reduce ions

CEPC High Luminosity Parameters after CDR

	tt	*Higgs*	*W*	*Z*	
Number of IPs	2	2	2	2	
Energy (GeV)	180	120	80	45.5	
Circumference (km)	100	100	100	100	
SR loss/turn (GeV)	8.53	1.73	0.33	0.036	
Half crossing angle (mrad)	16.5	16.5	16.5	16.5	
Piwinski angle	1.16	4.87	9.12	24.9	
N_e/bunch (10^{10})	20.1	16.3	11.6	15.2	
Bunch number (bunch spacing)	37 (4.45μs)	214 (0.7us)	1588 (0.2μs)	3816 (86ns)	11498 (26ns)
Beam current (mA)	3.5	16.8	88.5	278.8	839.9
SR power /beam (MW)	**30**	**30**	**30**	**10**	**30**
Bending radius (km)	10.7	10.7	10.7	10.7	
Phase advance of arc cell	90°/90°	90°/90°	90°/90°	60°/60°	
Momentum compaction (10^{-5})	0.73	0.73	0.73	1.48	
β_{IP} x/y (m)	1.0/0.0027	0.33/0.001	0.33/0.001	0.15/0.001	
Emittance x/y (nm)	1.45/0.0047	0.68/0.0014	0.28/0.00084	0.27/0.00135	
Transverse σ_{IP} (um)	37.9/0.11	15.0/0.037	9.6/0.029	6.36/0.037	
ξ_x/ξ_y/IP	0.076/0.106	0.018/0.115	0.014/0.13	0.0046/0.131	
V_{RF} (GV)	9.52	2.27	0.47	0.1	
f_{RF} (MHz) (harmonic)	650 (216816)	650 (216816)	650 (216816)	650 (216816)	
Nature bunch length σ_z (mm)	2.23	2.25	2.4	2.75	
Bunch length σ_z (mm)	2.66	4.42	5.3	9.6	
HOM power/cavity (kw)	**0.45 (5cell)**	**0.48 (2cell)**	**0.79 (2cell)**	**2.0 (2cell)**	**3.02 (1cell)**
Energy spread (%)	0.17	0.19	0.11	0.12	
Energy acceptance requirement (DA) (%)	2.0	1.7	1.2	1.3	
Energy acceptance by RF (%)	2.61	2.5	[illegible]	1.48	
Lifetime (hour)	0.59	0.35	1.3	1.7	1.4
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**0.5**	**5.0**	**18.7**	**35.0**	**105.5**

Physics motivation

TPC limitations for Z

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

MOST1

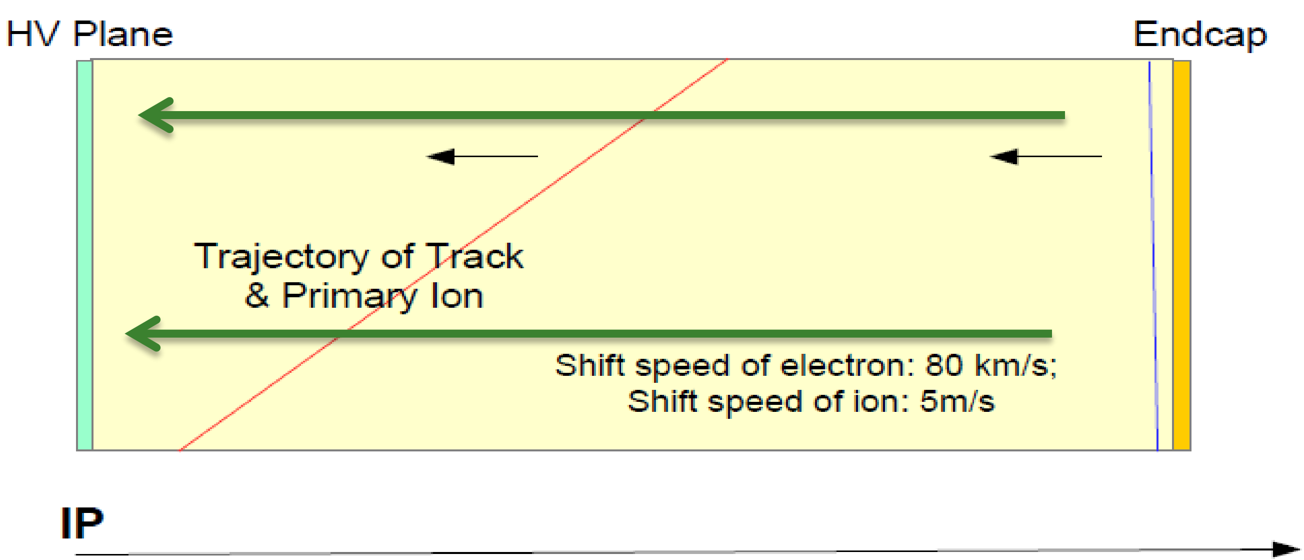
NSFC

MOST1

Updated Parameters of Collider Ring since CDR

	Higgs		Z (2T)	
	CDR	Updated	CDR	Updated
Beam energy (GeV)	120	-	45.5	-
Synchrotron radiation loss/turn (GeV)	1.73	1.68	0.036	-
Piwinski angle	2.58	3.78	23.8	33
Number of particles/bunch N_e (10^{10})	15.0	17	8.0	15
Bunch number (bunch spacing)	242 (0.68μs)	218 (0.68μs)	12000	15000
Beam current (mA)	17.4	17.8	461.0	1081.4
Synchrotron radiation power /beam (MW)	30	-	16.5	38.6
Cell number/cavity	2	-	2	1
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.33/0.001	0.2/0.001	-
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.89/0.0018	0.18/0.0016	-
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	17.1/0.042	6.0/0.04	-
Bunch length σ_z (mm)	3.26	3.93	8.5	11.8
Lifetime (hour)	0.67	0.22	2.1	1.8
Luminosity/IP L (10^{34} cm^{-2}s^{-1})	2.93	5.2	32.1	101.6

Luminosity increase factor: × 1.8 × 3.2

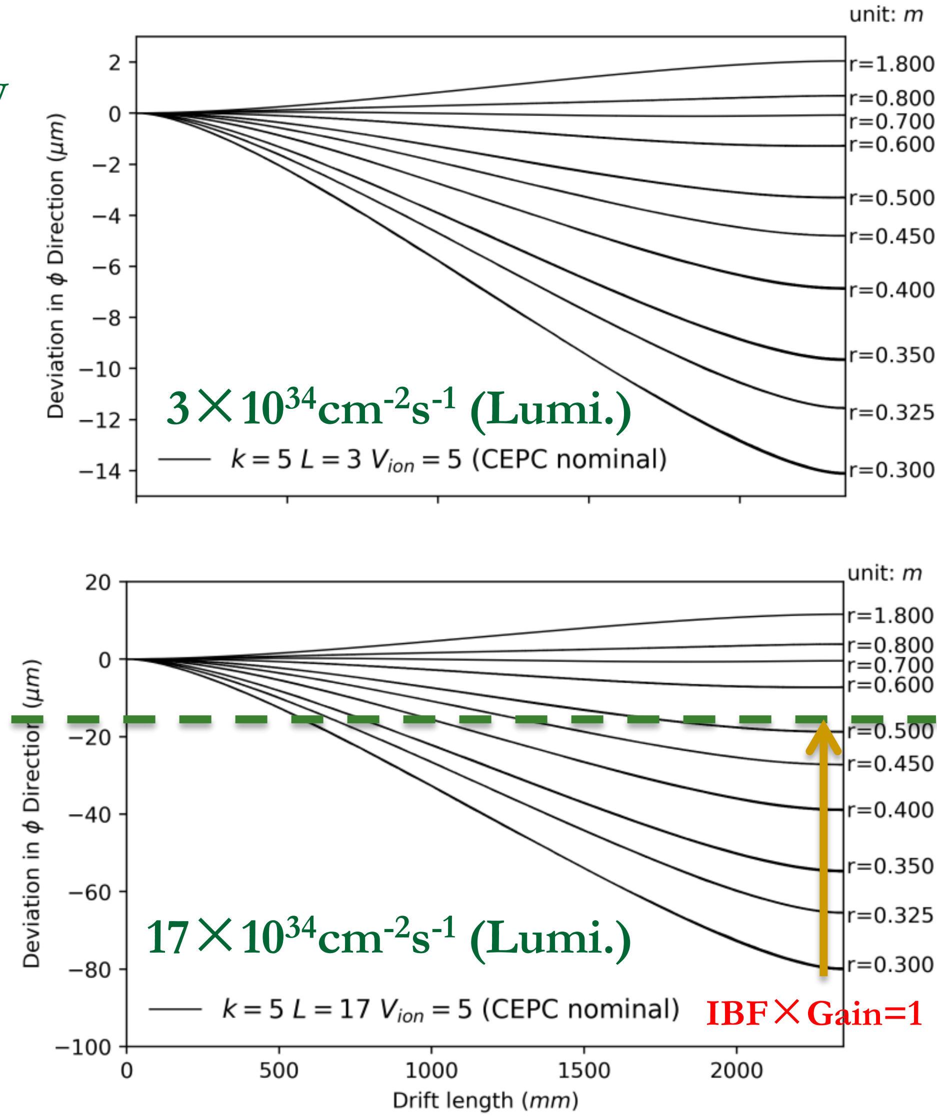


TPC detector concept

IBF simulation study at Z

DOI: 10.1142/S0217751X19400165, 2019
DOI: 10.1088/1748-0221/12/07/P07005, 2017

- Goal:
  - Operate TPC at higher luminosity
  - No Gating options
- Simulation
  - IBF×Gain default as the factor of 5
  - 9 thousand Z to qq events
  - 60 million hits are generated in sample
  - Average hit density: 6 hits/mm^2
  - Voxel size: 1mm×6mm ×2mm
  - Average voxel occupancy: 1.33×10^{-8}
  - Voxel occupancy at TPC inner most layer: ~2×10^{-7}
  - Validated with 3 ions disks
  - Simulation of the multi ions disk in chamber under the continuous beam structure
  - Without the charge of the beam-beam effects in TPC



Deviation with the different TPC radius

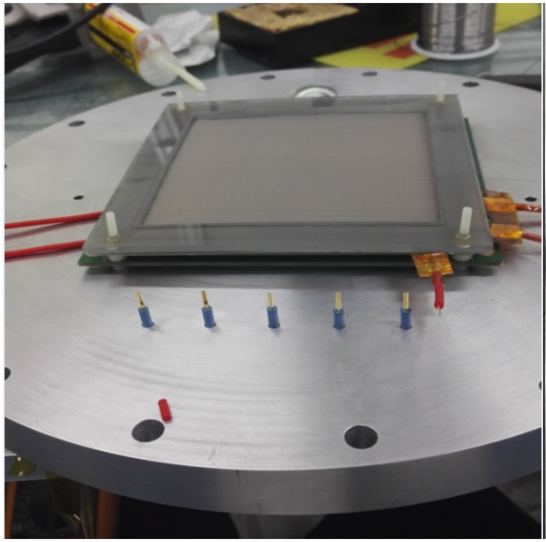
- **TPC module R&D**

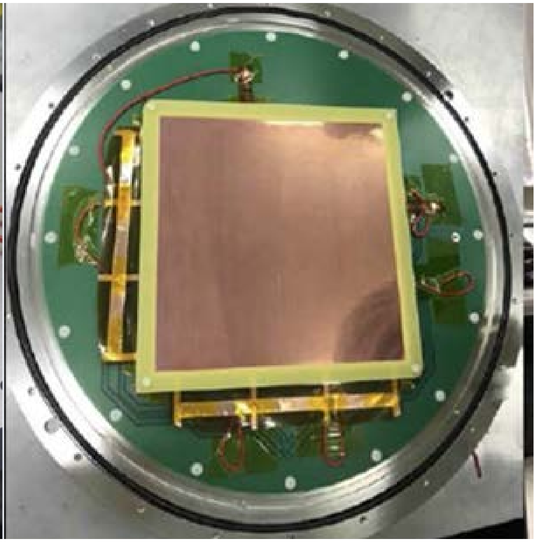
TPC detector module@ IHEP

- 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
  - Pixel option for the consideration in 2020

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
DOI: 10.1142/S2010194518601217 (SCI) 2018
DOI: 10.1088/1748-0221/13/04/T04008 (SCI) 2018
DOI: 10.1007/978-981-13-1316-5_20 (SCI) 2018

$50\times50mm^2$ 2015-2016 → $100\times100mm^2$ 2017-2018 → $200\times200mm^2$ 2019-2020

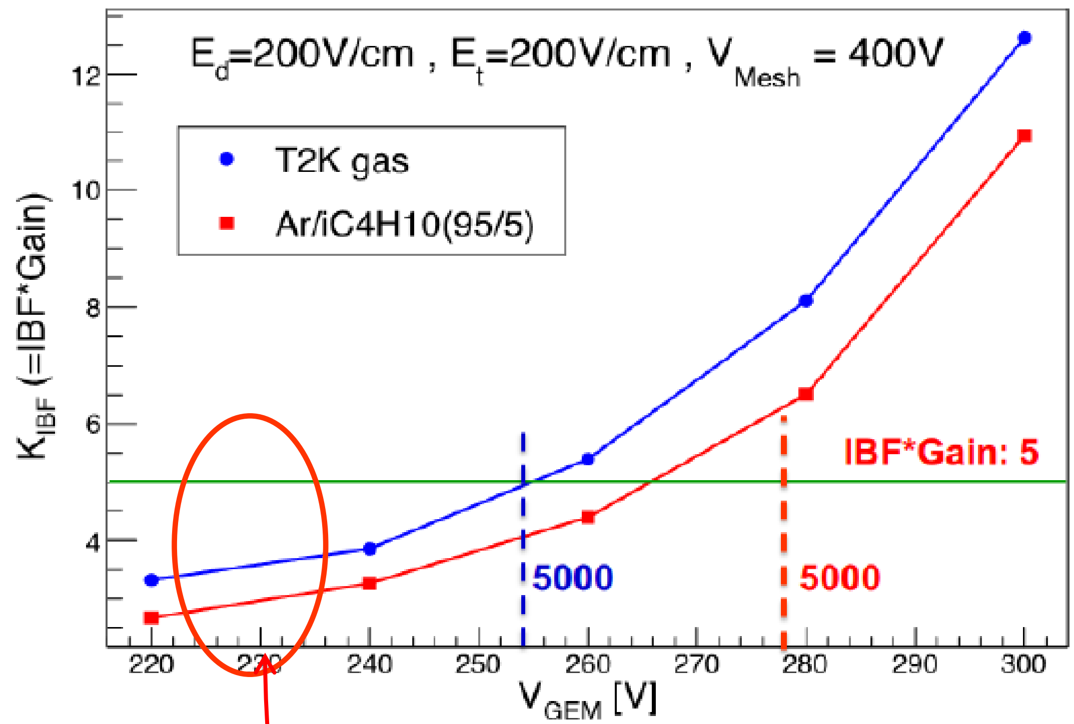




GEM-MM detector cathode

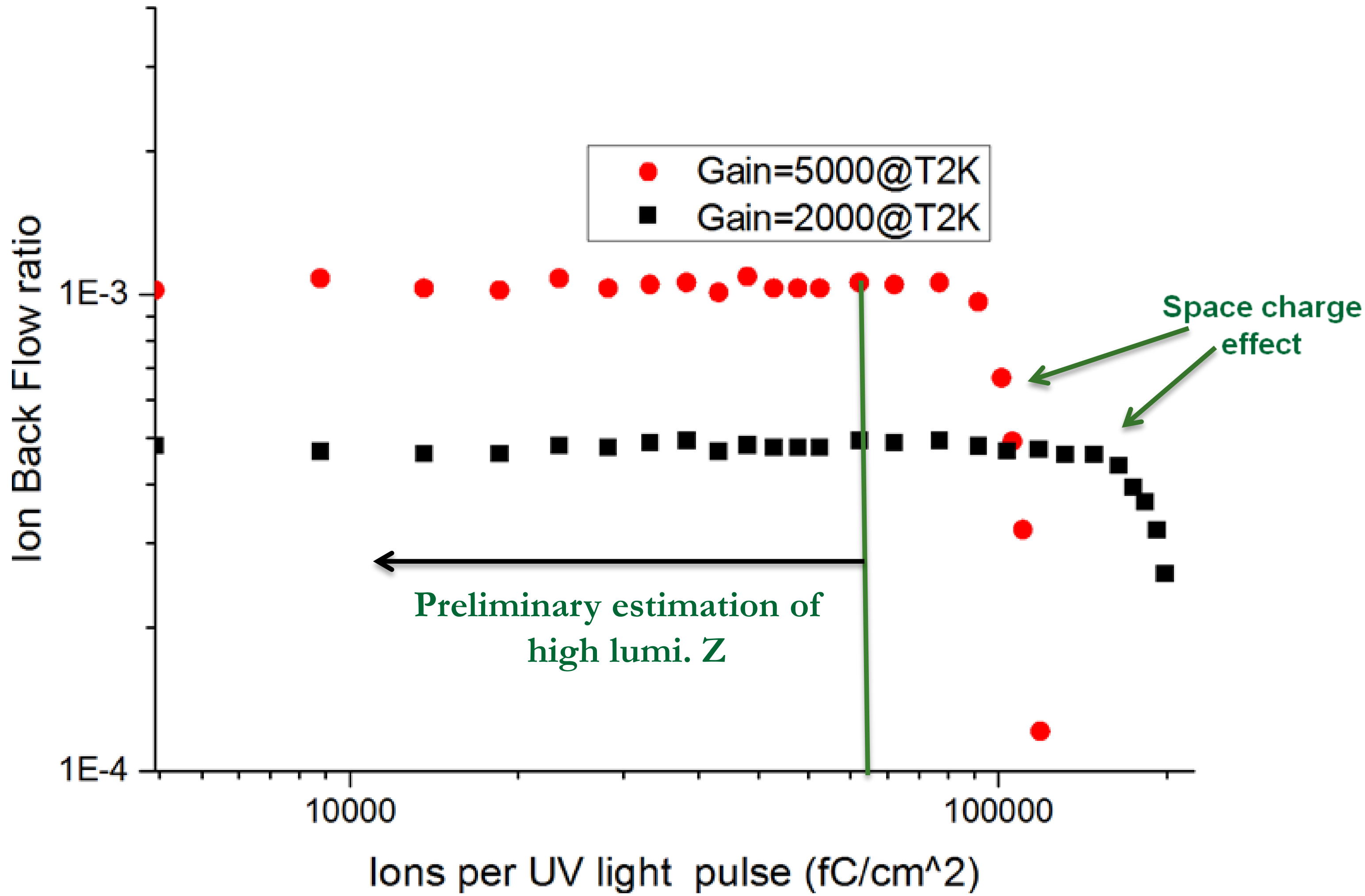
GEM+MM

Micronegas + GEM detector module @IHEP



- IBF×Gain ratio can meet less than 2 at the lower gain under two mixture gases
- Lower gain and lower IBF ratio

Space charge effect at the different gain



- Preliminary estimation of the high luminosity Z
- There are more safe factor when the detector will run at the lower gain (eg.2000-3000)

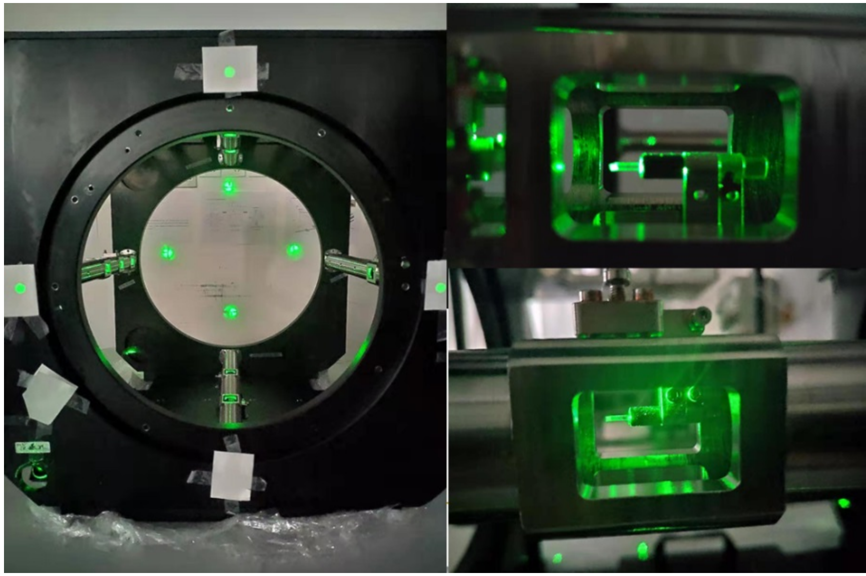
Different concepts with IBF suppression

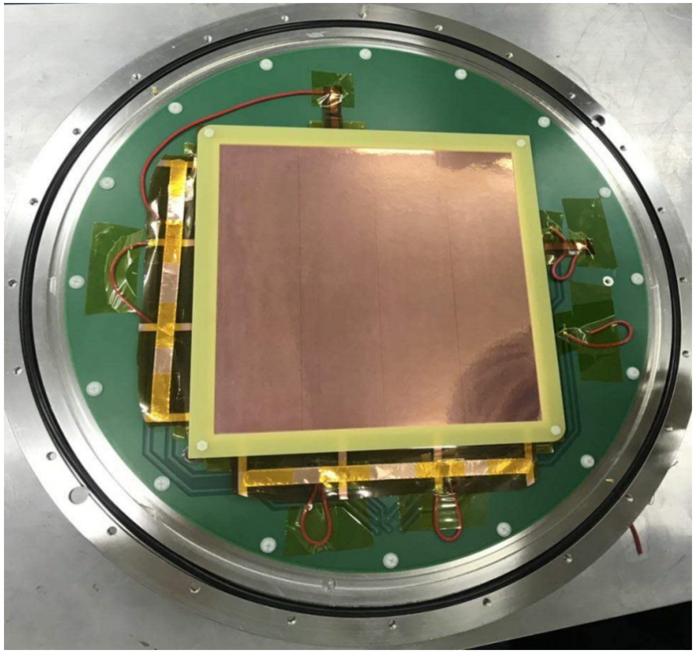
Pixel TPC with double meshes	Triple or double GEMs	Resistive Micromegas	GEM+ Micromegas	Double meshes Micromegas
IHEP, Nikehf	KEK, DESY	Saclay	IHEP	USTC
Pad size: 55um-150um square	Pad size: 1mm×6mm	Pad size: 1mm×6mm	Pad size: 1mm×6mm	Pad size: 1mm×6mm (If resistive layer)
Advantage for TPC: Low gain: 2000 IBF×Gain: -1	Advantage for TPC: Gain: 5000-6000 IBF×Gain: <10	Advantage for TPC: Gain: 5000-6000 IBF×Gain: <10	Advantage for TPC: Gain:5000-6000 IBF×Gain: <5	Advantage for TPC: High gain: 10^4 Gain: 5000-6000 IBF×Gain: 1-2
Electrons cluster size for FEE: About Ø200um	Electrons cluster size for FEE: About Ø5mm	Electrons cluster size for FEE: About Ø8mm	Electrons cluster size for FEE: About Ø6mm	Electrons cluster size for FEE: About Ø8mm
Integrated FEE in readout board Detector Gain：2000	FEE gain: 20mV/fC Detector Gain：5000-6000	FEE gain: 20mV/fC Detector Gain：5000-6000	FEE gain: 20mV/fC Detector Gain：5000-6000	FEE gain: 20mV/fC Detector Gain：5000-6000

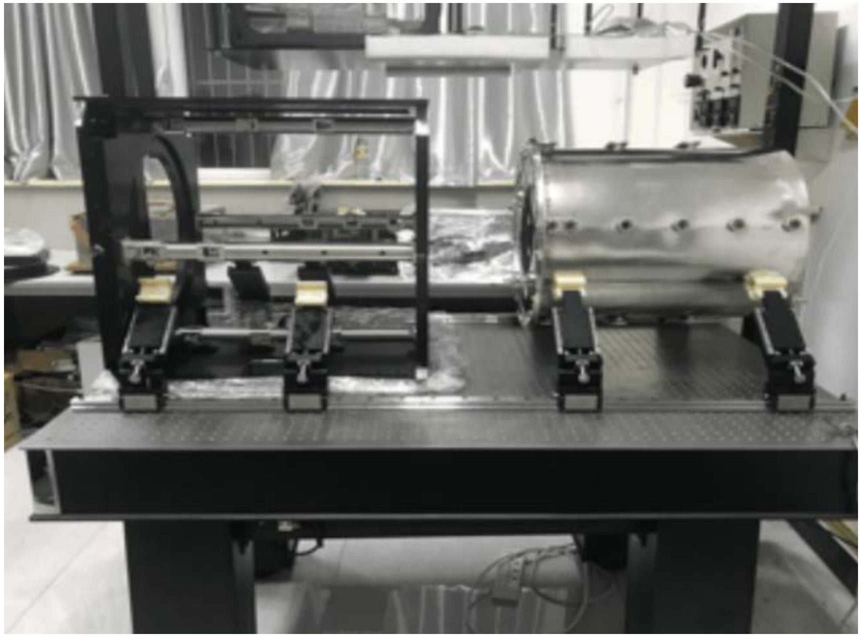
- **TPC prototype R&D**

TPC detector prototype

- Study of TPC prototype with 42 UV laser beams
- Main parameters
  - Drift length: ~500mm, Active area: 200mm^2
  - Integrated 266nm laser beam
  - GEMs/Micromegas as the readout







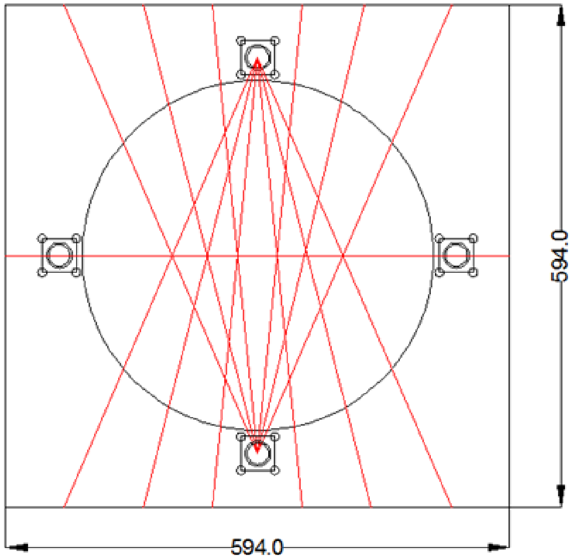
Electronics and DAQ

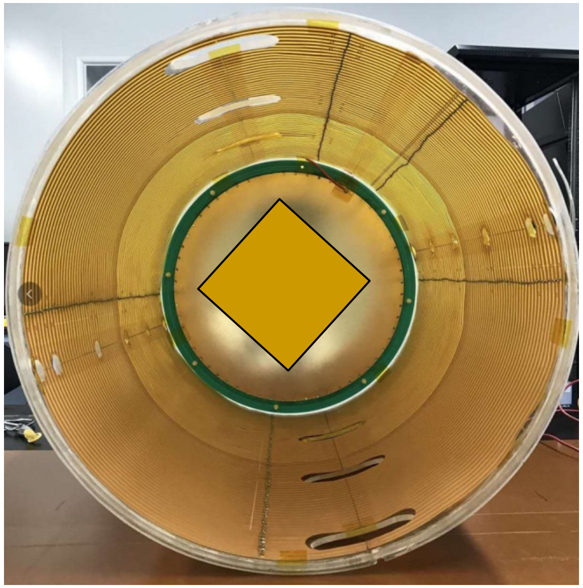
- Amplifier and FEE
  - CASAGEM chip
  - 16Chs/chip
  - 4chips/Board
  - Gain: 20mV/fC
  - Shape time: 20ns

- DAQ
  - FPGA+ADC
  - 4 module/board
  - 64Chs/module
  - Sample: 40MHz
  - 1280chs

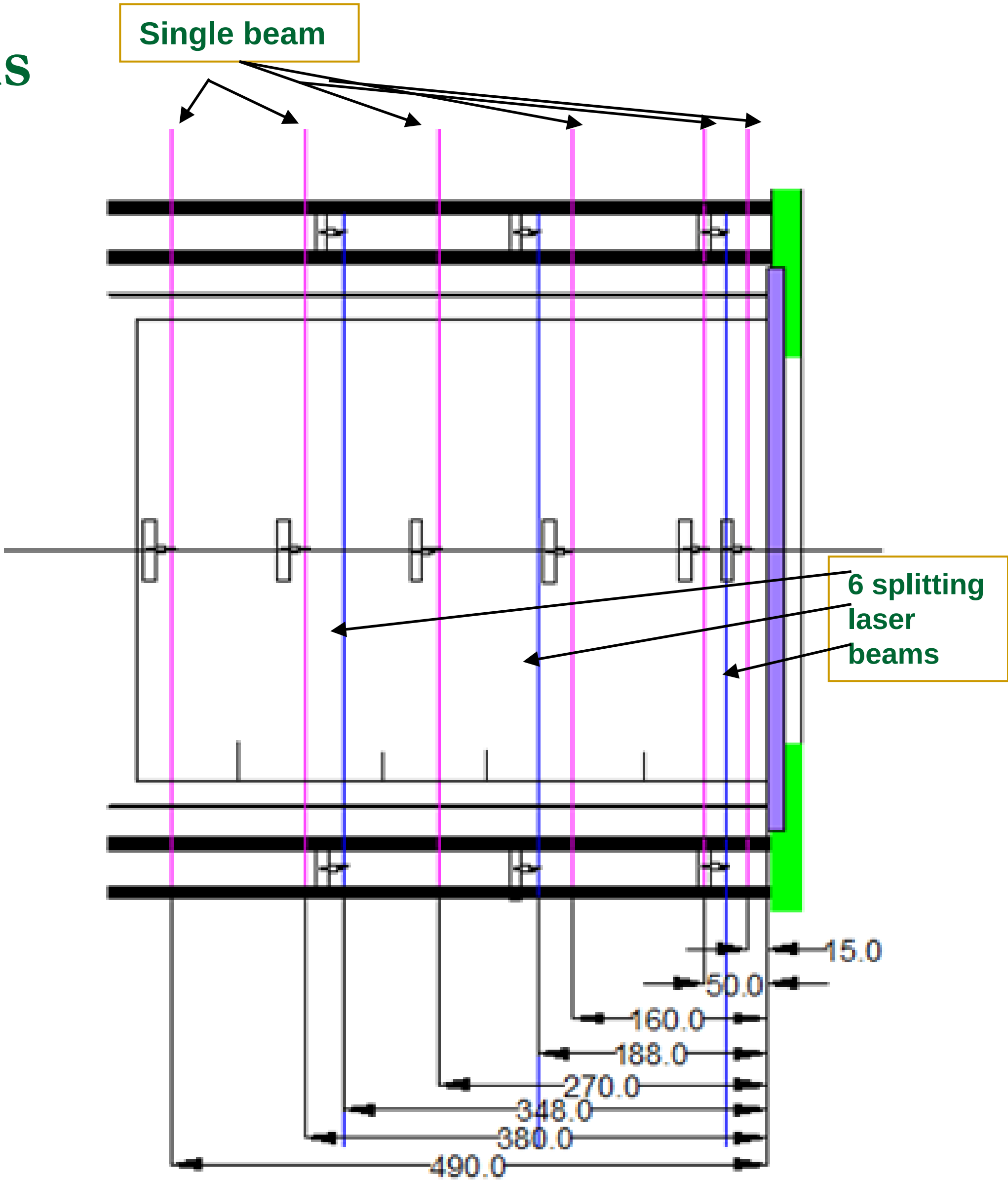
FEE Electronics and DAQ setup photos

Layout of UV laser beams



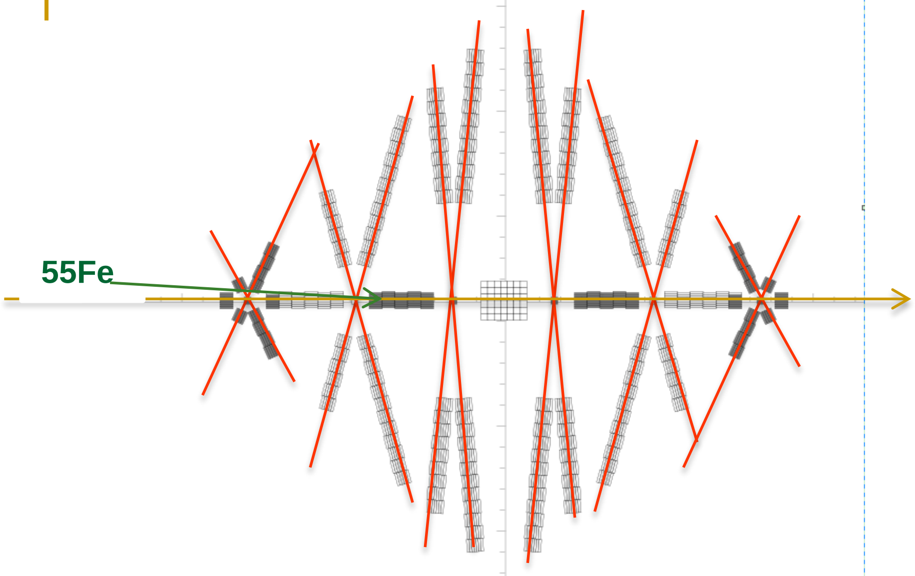


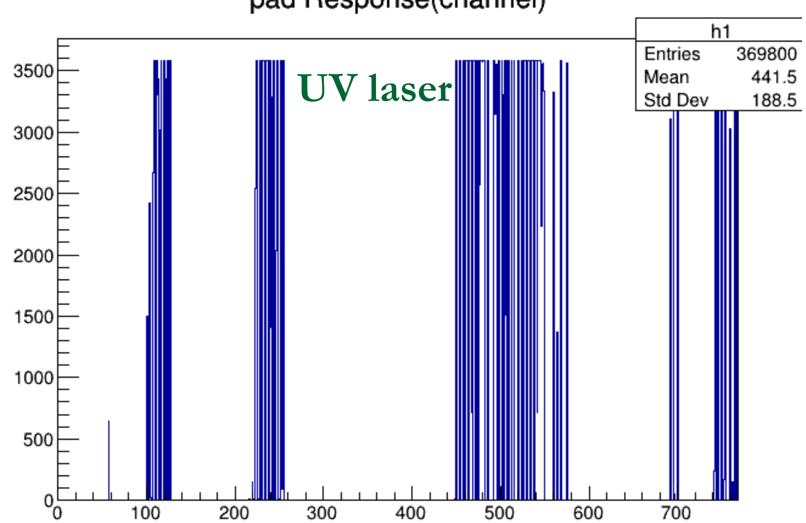
Laser map in X-Y direction

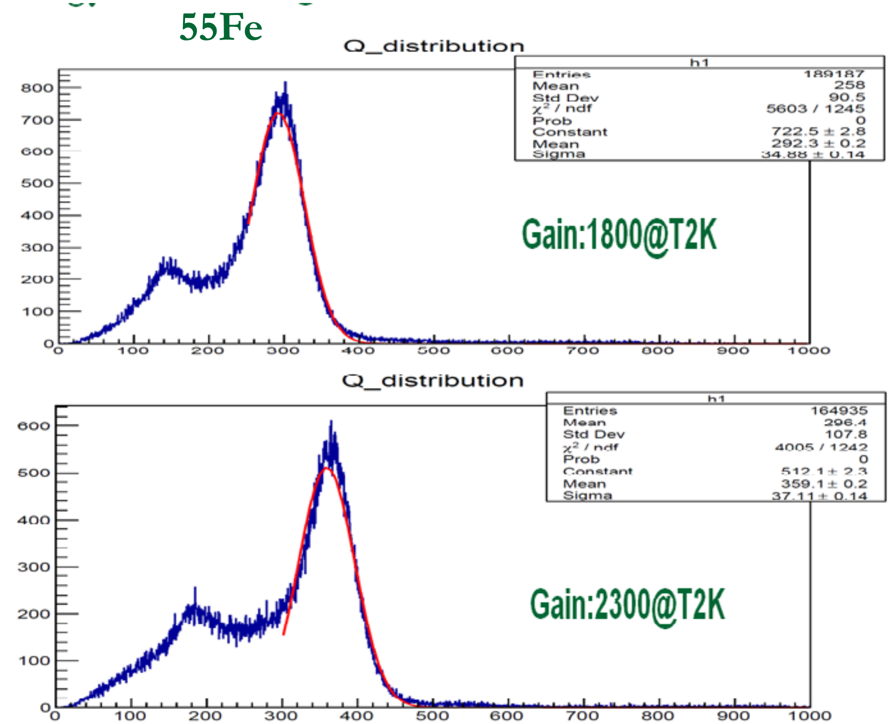


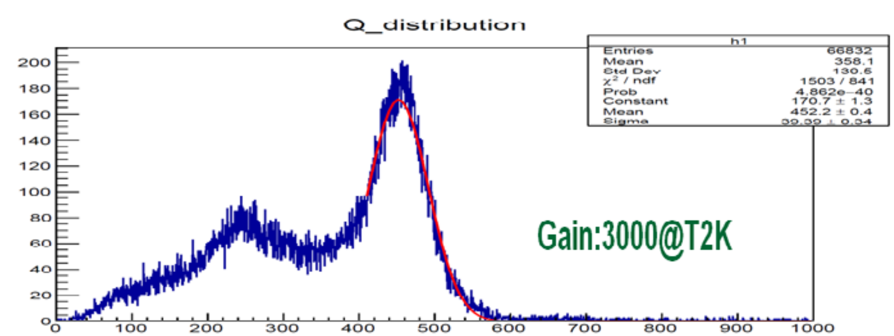
Laser map along drift length

Energy spectrum@T2K gas



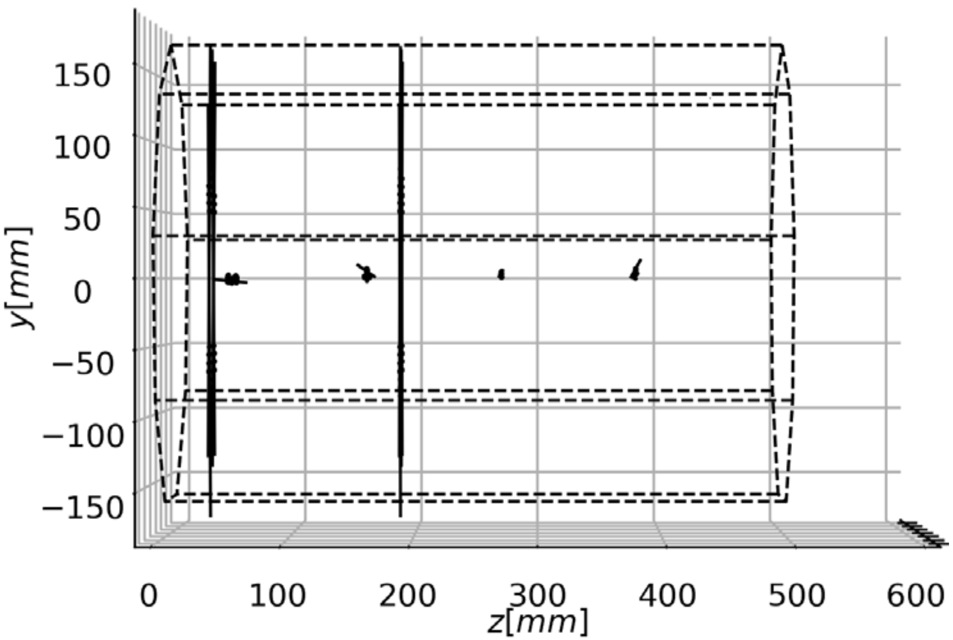


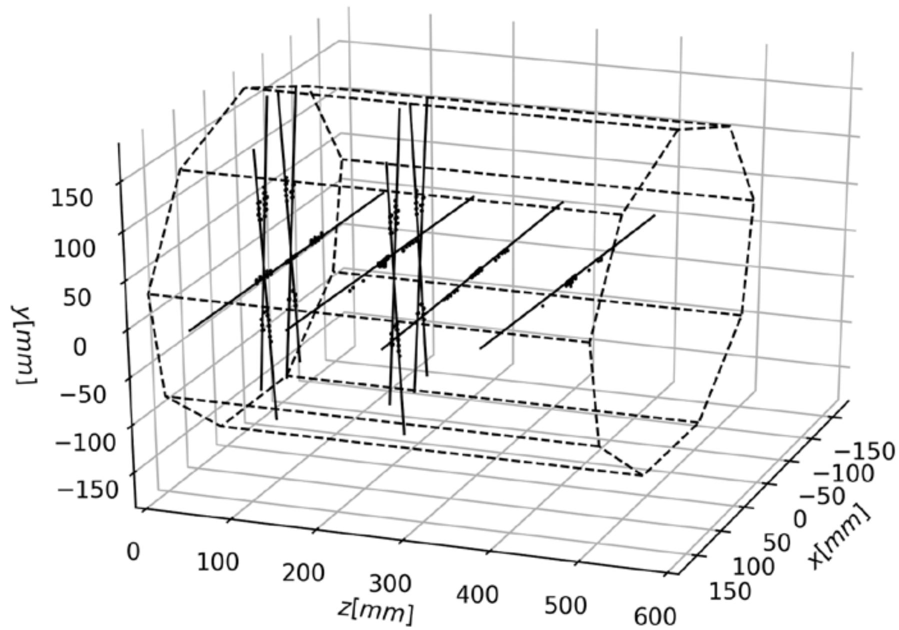




All pads response and energy spectrum @laser and 55Fe

Laser tracks in chamber@T2K gas

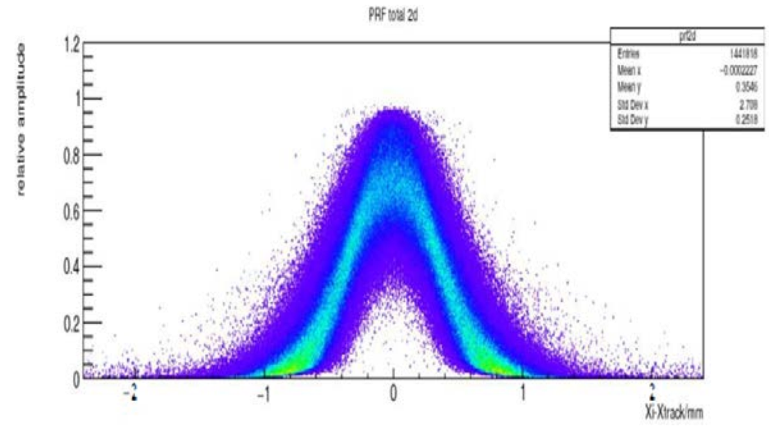


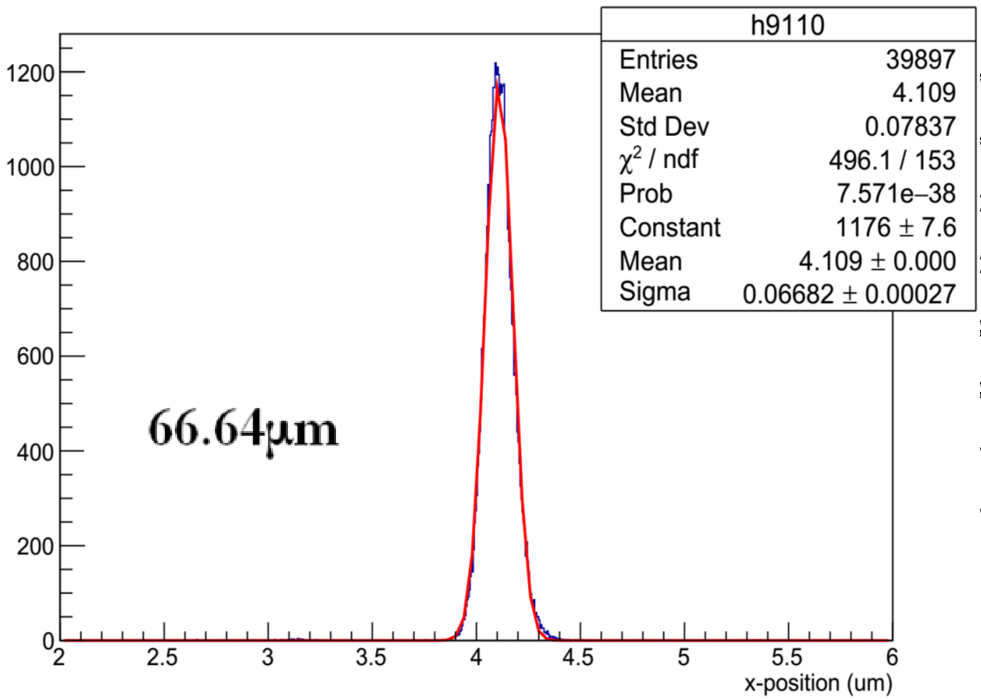


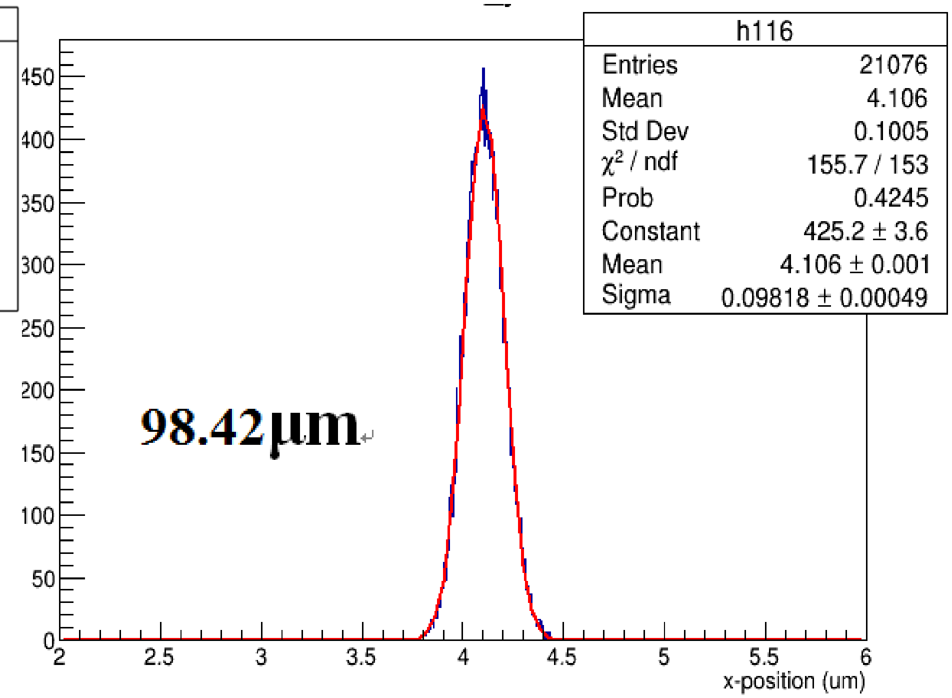
- **Same of working gas@T2K, same of high voltage, same of test conditions**
- **Different of GEMs@ 320V**
- **Triple GEMs to double GEMs**
- **No discharge**

Space resolution

$$PRF(x, r, w) = \frac{\exp[-4\ln 2(1-r)x^2/w^2]}{1+4rx^2/w^2}$$

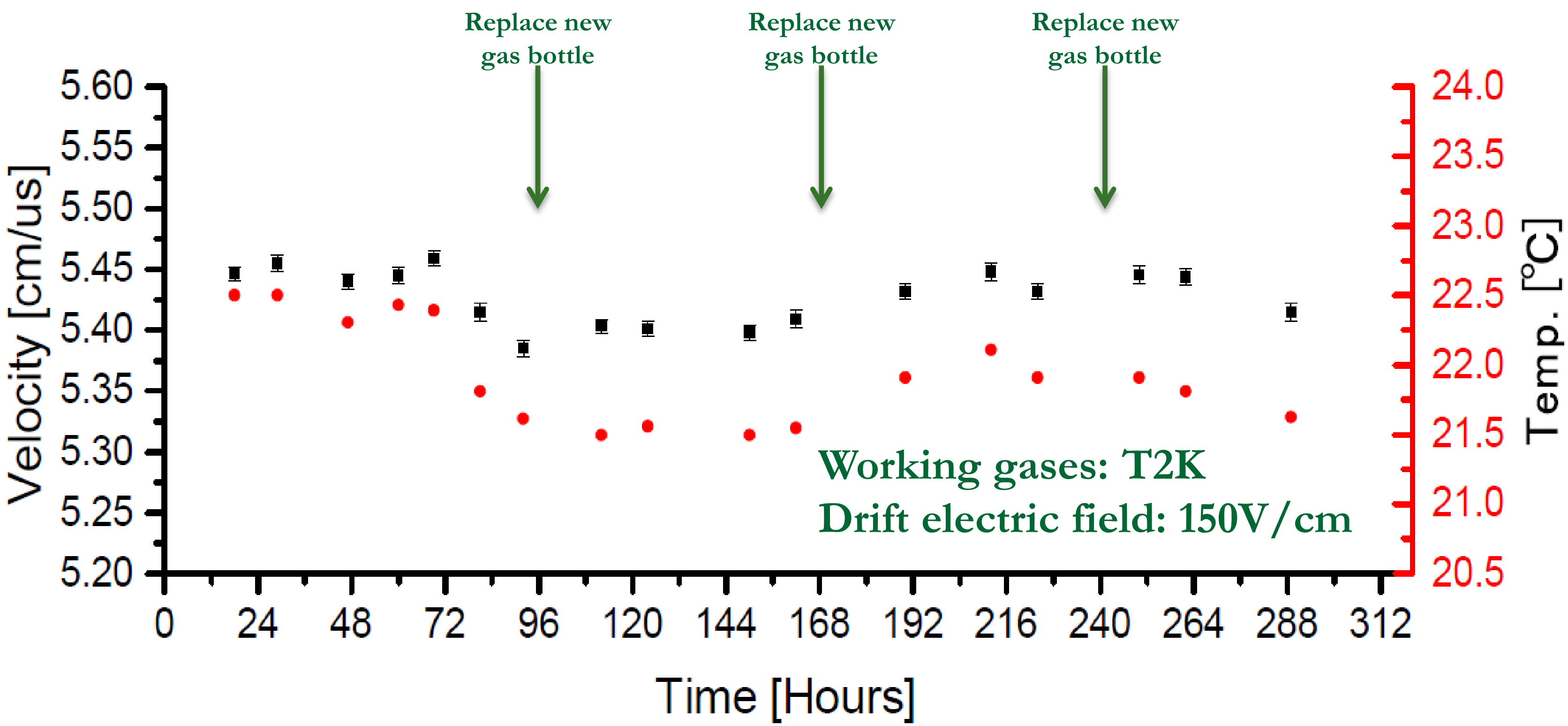






Space resolution at the different drift length
Left(drift length: 50mm) Right(drift length: 270mm)

Drift velocity measurement



- Three weeks of continuous testing (Data of E_{drift}=220V/cm is analyzing)
- Room temperature recorded
- Comparison of the drift velocity and the temperature
- Simulation of some influencing factors using Garfield/Gariflield++ software

Conclusion: 266nm UV laser can work well when it can be as the online monitor option.

- **FEE ASIC chip R&D**

Current TPC readout ASICs

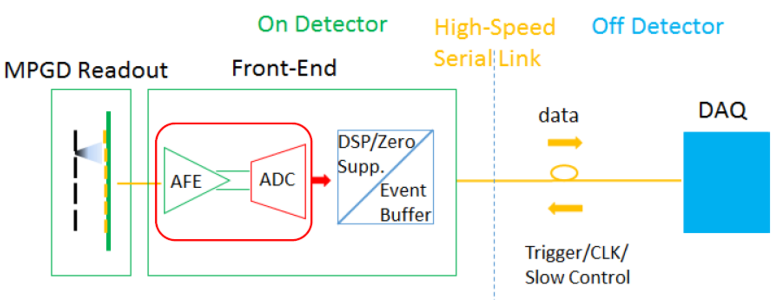
- Waveform sampling (8-10 bit, ~10MS/s) is required for TPC signal processing
- Direct ADC sampling is more preferable than SCA for high rate applications
- Lower power consumption → less cooling → less material

	PASA/ALTRO	AGET	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 x 10^5	1.25 x 10^5	1-2 x 10^6	5.7 x 10^5
Readout Chamber	MWPC	MicroMegas	GEM/MicroMegas	GEM
Gain	12 mV/fC	0.2-17 mV/fC	12-27 mV/fC	20/30 mV/fC
Shaper	CR-$(RC)^4$	CR-$(RC)^2$	CR-$(RC)^4$	CR-$(RC)^4$
Peaking time	200 ns	50 ns-1us	30-120 ns	80/160 ns
ENC	385 e	850 e @ 200ns	520 e	482 e @ 180ns
Waveform Sampler	ADC	SCA	ADC	ADC
Sampling frequency	10 MSPS	1-100 MSPS	40 MSPS	20 MSPS
Dynamic range	10 bit	12 bit(external)	10 bit	10 bit
Power consumption	32 mW/ch	<10 mW/ch	47.3 mW/ch	8 mW/ch
CMOS Process	250 nm	350 nm	130 nm	130 nm

Specifics of ASIC using 65nm

- In order to reduce the power consumption:
  - Using more advanced 65 nm CMOS process favoring digital logics
  - Reducing analog circuits:
    - CR-(RC)^n →CR-RC, moving high order shaping to digital domain
    - ADC structure : pipeline → SAR (Successive Approximation Register)
- So far only the AFE and the ADC parts have been implemented

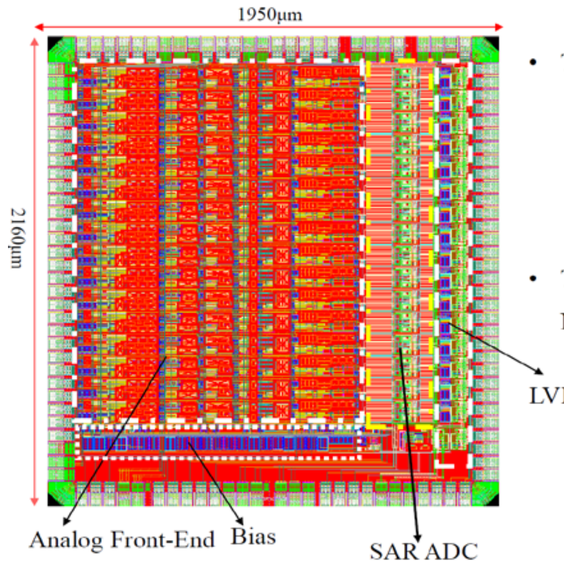
AFE(Analog Front-End)	
Signal Polarity	Negative
Detector Capacitance	5-20 pF
Shaper	CR-RC
Shaping Time	160 ns
ENC (Equivalent Noise Charge)	<500 e @ 10pF
Dynamic Range	120 fC max.
Gain	10-40 mV/fC
INL (Integrated Non-Linearity)	<1%
Crosstalk	<1%
Power Consumption (AFE)	<2.5 mW/ch



SAR-ADC	
Input Range	-0.6 V ~ 0.6 V diff.
Resolution	10 bit
Sampling Rate	40 MS/s
DNL	<0.6 LSB
INL	<0.6 LSB
SFDR @ 2MHz, 40MSPS	68 dBc
SINAD	57 dB
ENOB	>9.2 bit @ 2MHz
Power Consumption (ADC)	<2.5 mW/ch

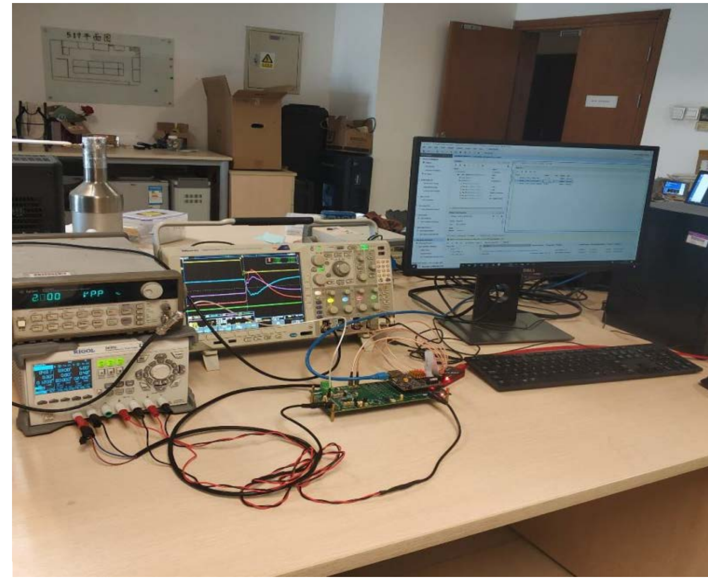
- AFE + waveform sampling ADC + direct output
- Process: TSMC 65nm LP
- Power supply: 1.2V

Tests of the ASIC chip

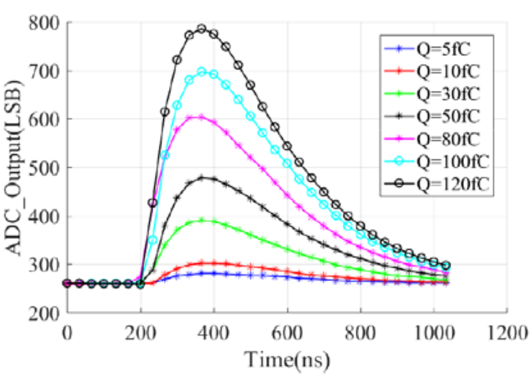


Layout of ASIC chip

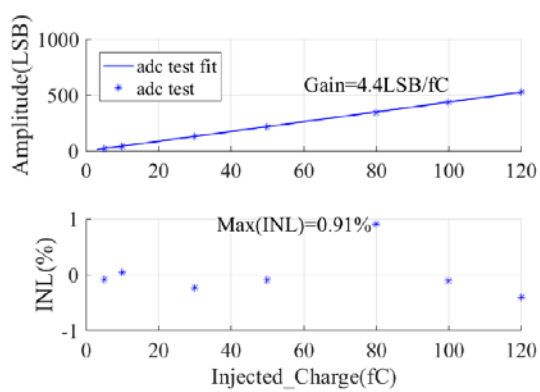
- The floor plan in layout :
  - The die size of 1950 μm x 2160 μm
  - Analog Front-End , SPI, SAR ADC, LVDS driver are supplied by separate power
- The ASIC have been taped out in November, 2019 and is being evaluated



- Transient outputs



- The linearity @ gain = 10 mV/fC



Gain = 4.4 LSB/fC = 4.4 x 2.34 mV/fC = 10.3 mV/fC

Test of the signals

Results of ASIC chip

- A 16 channel low power readout ASIC for TPC readout have been developed
  - The power consumption is 2.33 mW/channel:
    - P_{AFE}=1.43 mW/channel
    - P_{ADC} = 0.9 mW/channel @ 40MS/s
  - ENC = 852 e @ Cin=2 pF, gain=10 mV/fC and can be reduced to 474 e using digital trapezoidal filter
- Future Plan
  - More ASIC evaluations: higher sampling rate, more detailed noise test, test with detectors…
  - Low power digital filter and data compression in FPGA/ASIC

Summary

Requirements and critical challenges for the high luminosity motivation:

- IBF×Gain should be considered at the high luminosity
- Some motivations of TPC detector for collider at Z pole run listed.

TPC module and prototype R&D:

- TPC can meet most requirements of PID and moment resolution, and others should be optimized and R&D
- Concerning TPC technology R&D in ILD collaboration, IHEP will continuously collaborated with LCTPC
- The calibration and alignment methods of the narrow UV laser beam considered for further R&D

- **TPC prototype R&D**