Status and progress of TPC technology R&D for e^+e^- collider

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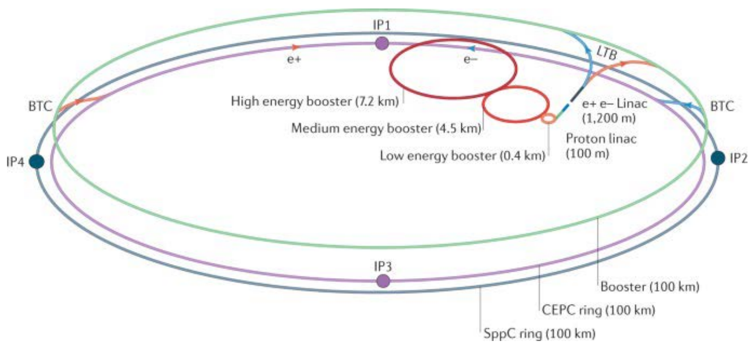
Outline

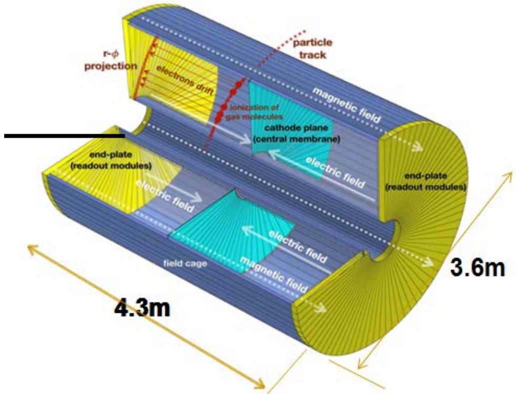
- Physics motivation
- TPC technology R&D
- Some related TPC R&D
- Summary

TPC as key roles@ Future e^+e^- Colliders

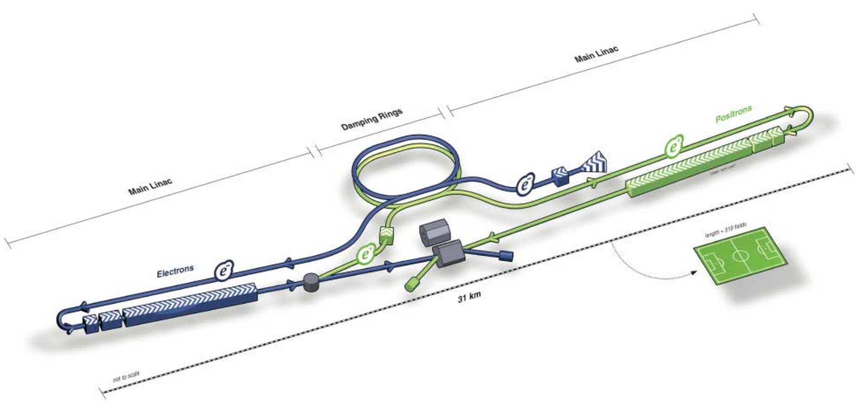
Beam parameters	ILC		CLIC			FCC-ee			CepC	
Energy(TeV)	0.25	0.5	0.38	1.5	3	0.091	0.24	0.36	0.091	0.24
Luminosity (x 10^{34} cm^{-2} s^{-1}) per IP	1.35	1.8	1.5	3.7	5.9	230	8.5	1.7	32	1.5
Bunch train frequency (Hz)	5		50							
Bunch separation (ns)	554		0.5			20	994	3000	25	680
Number of bunches / train - beam	1312		312	312		16640	393	48	12000	242



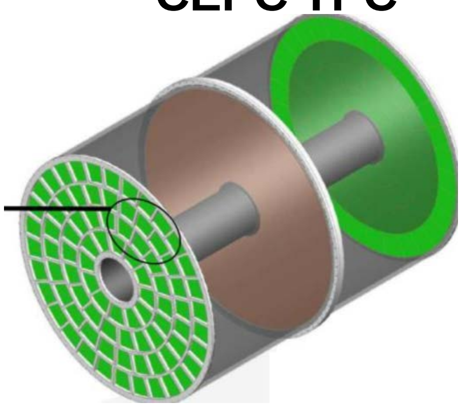
CEPC



CEPC TPC



ILC



ILD TPC

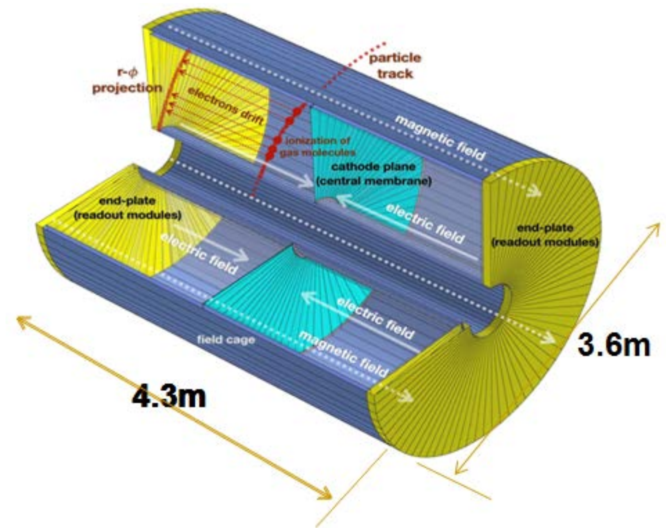
Gaseous Tracking Systems @ Future Colliders

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
CEPC TPC DETECTOR START: > 2030	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 2x10 m^2 Single unit detect: up to 0.04 m^2	**Max.rate@Z**: 100 kHz/cm^2 **Spatial res.:** ~100µm **Time res.:** ~ 100 ns **dE/dx:** <5%	- Higgs run - Z pole run - Continues readout - Low IBF and dE/dx
ILC TPC DETECTOR: STARTt: > 2035	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 20 m^2 Single unit detect: ~ 400 cm^2 (pads) ~ 130 cm^2 (pixels)	**Max. rate**: < 1 kHz **Spatial res.:** <150µm **Time res.:** ~ 15 ns **dE/dx:** <5%	Si + TPC Momentum resolution : dp/p < $9*10^{-5}$ 1/GeV Power-pulsing
FCC-ee and/or CEPC IDEA CENTRAL TRACKER START: >2030	e+e- Collider Tracking/ Triggering	He based Drift Chamber	Total volume: 50 m^3 Single unit detect: (12 m2 X 4 m)	**Max. rate:** < 25 kHz/cm^2 **Spatial res.:** <100 µm **Time res.:** 1 ns **Rad. Hard.:** NA	Particle sepration with cluster counting at 2% level
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Main Tracker	Drift Chamber	Total volume: ~ 3.6 m^3	**Max. rate**: 1 kHz/cm^2 **Spatial res.:** ~100 µm **Time res.:** ~ 100 ns **Rad. Hard.:** ~ 1 C/cm	
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Inner Tracker	Inner Tracker / (cylindrical µRWELL, or TPC / MPDG read.	Total area: ~ 2 - 4 m^2 Single unit detect: 0.5 m^2	**Max. rate**: 50-100 kHz/cm^2 **Spatial res.:** ~<100 µm **Time res.:** ~ 5 -10 ns **Rad. Hard.:** ~ 0.1-1 C/cm^2	Challenging mechanics & mat. budget < 1% X_0
ELECTRON-ION COLLIDER (EIC) START: > 2025	Electron-Ion Collider Tracking	Barrel: cylindrical MM, µRWELL Endcap: GEM, MM, µRWELL	Total area: ~ 25 m^2	Luminosity (e-p): 10^{33} **Spatial res.:** ~ 50- 100 um **Max. rate**: ~ kHz/cm^2	Barrel technical challenges: low mass, large area Endcap: moderate technical challenges

TPC detector technology

Some advantages of TPC detector :

- Operation 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
- Readout options: pad and pixel

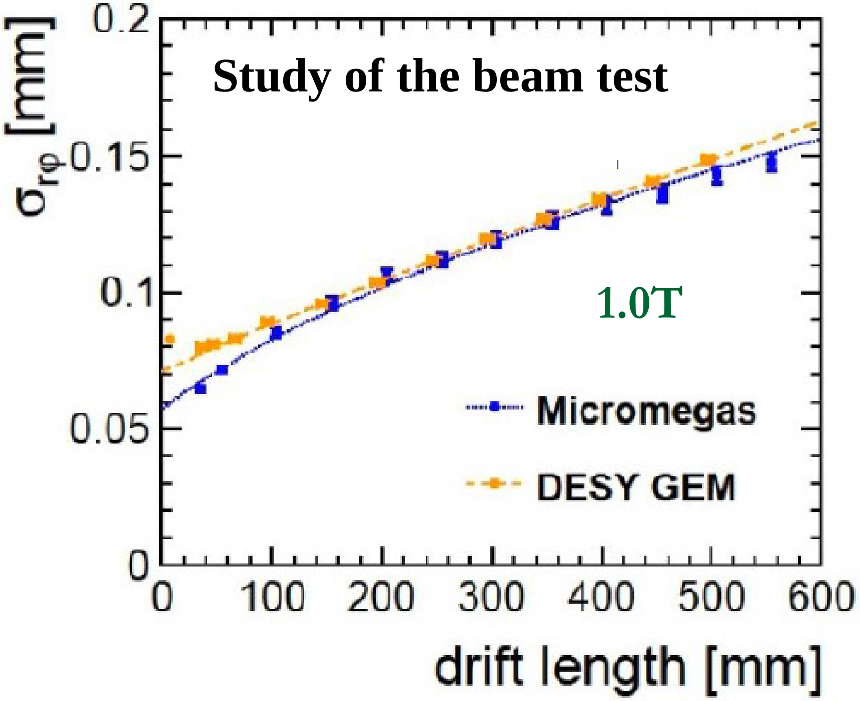


TPC detector concept

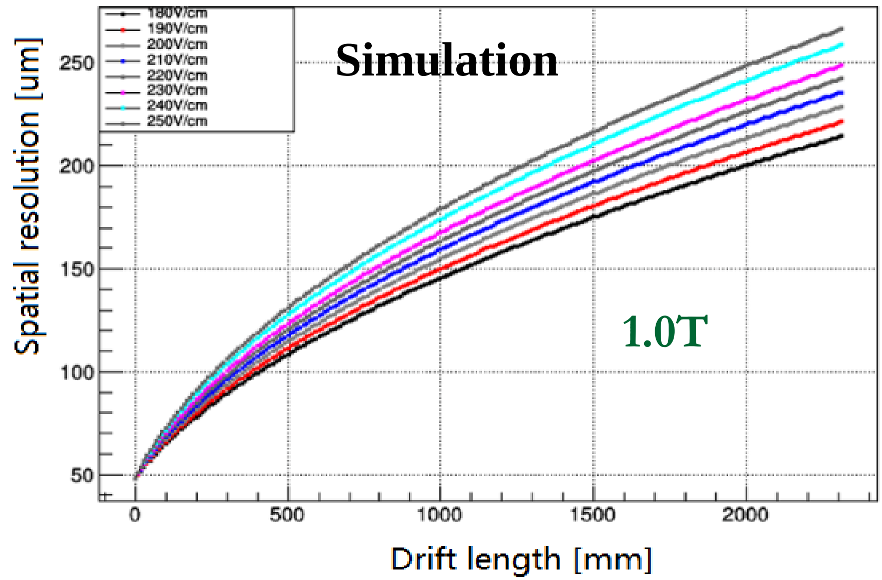
Momentum resolution (B=3.5T)	$\delta(^1/_{p_t} \approx 10^{-4}/GeV/c)$
δ_{point} in $r\Phi$	<100 μm
δ_{point} in rz	0.4-1.4 mm
Inner radius	329 mm
Outer radius	1800 mm
Drift length	2350 mm
TPC material budget	$\approx 0.05X_0$ incl. field cage $< 0.25X_0$ for readout endcap
Pad pitch/no. padrows	≈ 1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

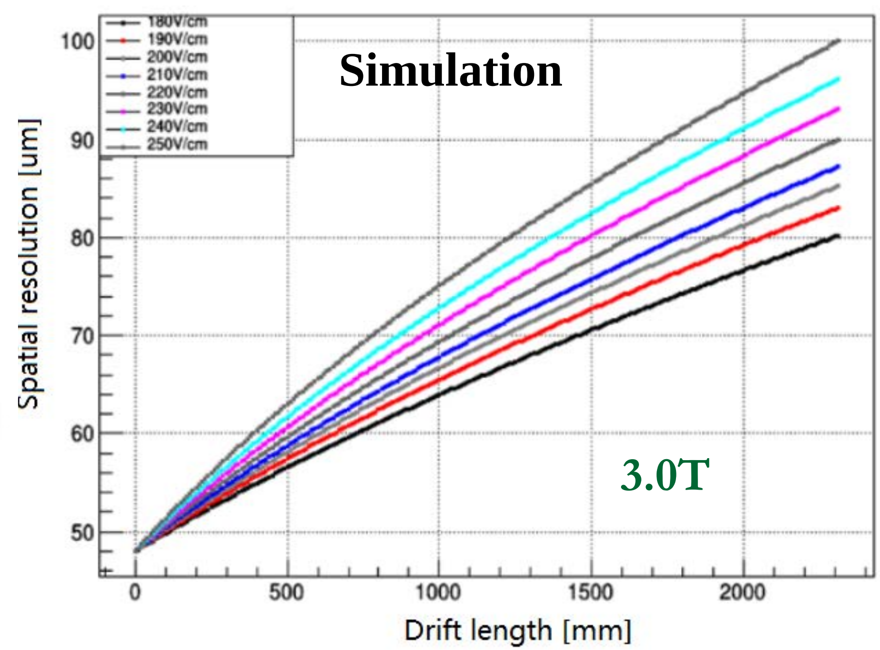
Motivation of spatial resolution (δ_x)

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\underbrace{\left(\frac{\alpha'\sigma_x}{BL^2}\right)^2\left(\frac{720}{N+4}\right)p_\perp^2}_{\text{measurements}} + \underbrace{\left(\frac{\alpha' C}{BL}\right)^2\frac{10}{7}\left(\frac{X}{X_0}\right)}_{\text{multiple scattering}}}$$



Large prototype@1.0T from LCTPC

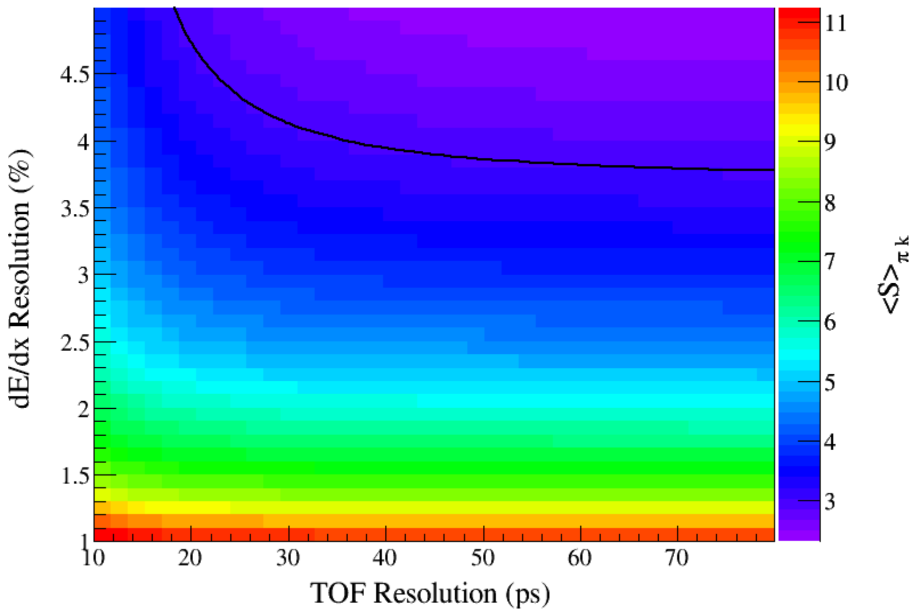


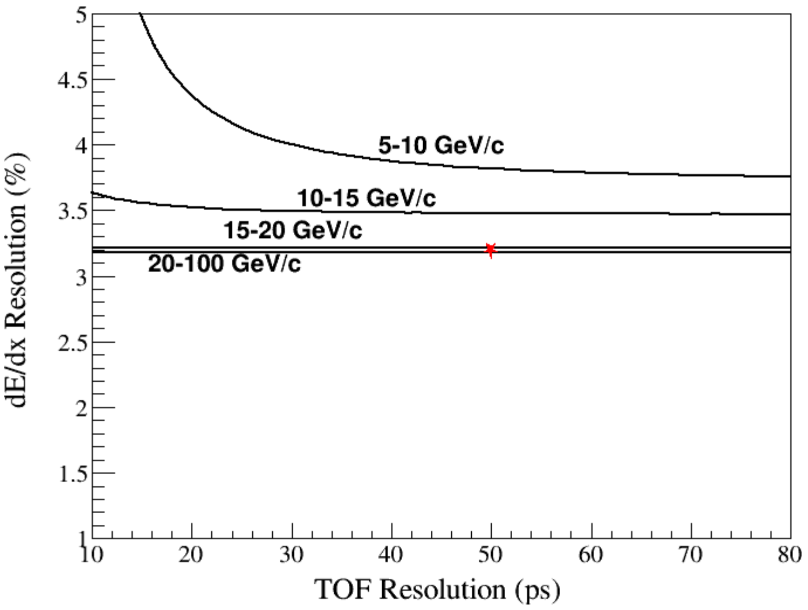


Motivation of Particle identification (dE/dx)

- Simulation results from CEPC
- Scan of the baseline detector concept performance
  - 3.2% dE/dx resolution
  - 50psTOF resolution

Zhiyang Yuan and Manqi Ruan





Particle identification from the experiments

$$\sigma_{dE/dx} = \sigma_0 N_{hits}^{-k}$$

Experiment	Readout	Points	Sample	$p(GeV/c)$	$(\sigma_I/I)_{MC}$	$(\sigma_I/I)_{exp}$
	Pad (mm)					
PEP-4 TPC	4	183	e	14.5	2.6%	3.5%
TOPAZ TPC	4	175	π	0.4-0.6	3.8%	4.5%
DELPHI TPC	4	192	π	0.4-0.6	5.4%	6.2%
ALEPH TPC	4	344	e	45.6	3.0%	4.4%
STAR TPC	12, 20	13,32	π	0.4-0.6	5.3%	6.8%
ALICE TPC	7.5, 10, 15	63,64,32	π	6.0	3.3%	5.0%
TPC for CEPC	1mm×6mm	220	K	5.0	3.1%	
	Pixel(μm)					
GridPix TPC for ILD	55×55	9500	e	2.5	/	4.1%

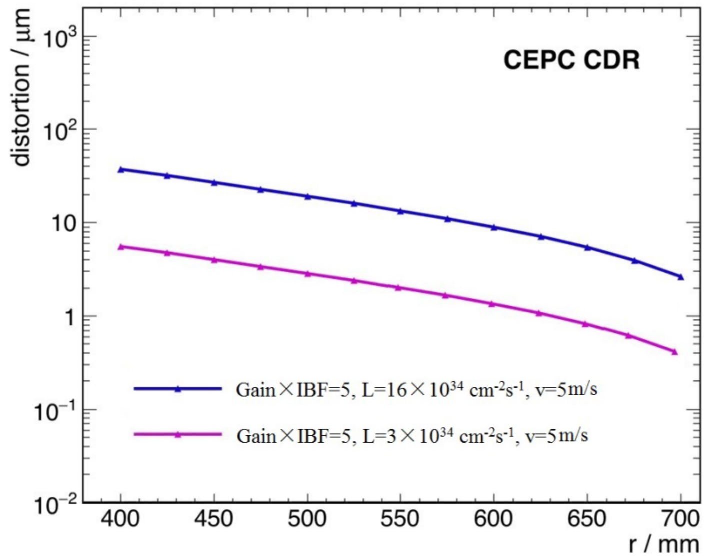
Status of TPC technology R&D

Goals:

- **Operate TPC at high luminosity ($\mathcal{L}$ = 32×1034 cm-2 s-1) at Z pole run (~10 kHz)**
- **No gating**
- **Maximal occupancy at TPC inner-most layer: ~10^{-5} (safe!)**
- **Rough estimations for primary ionisation⇒distortions < 10 μm (safe!)**
- **Total ions in chamber: Gain × IBF per primary ionization**
- **For Gain×IBF < 5 distortions < 40 μm(~50% of intrinsic resolution)**
- **UV laser mimic tracks without the beam to study the performance**

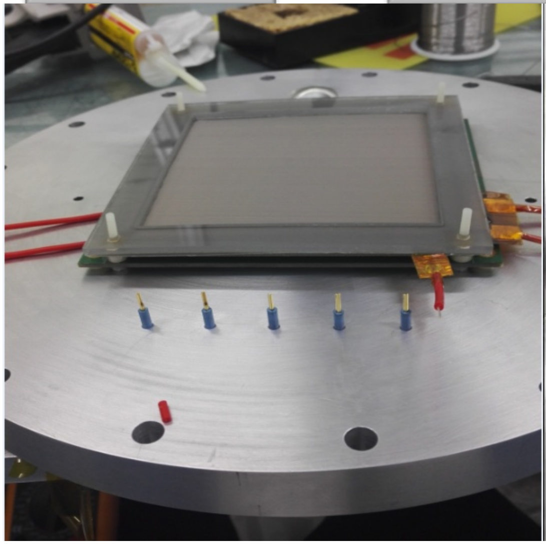
TPC detector module@IHEP

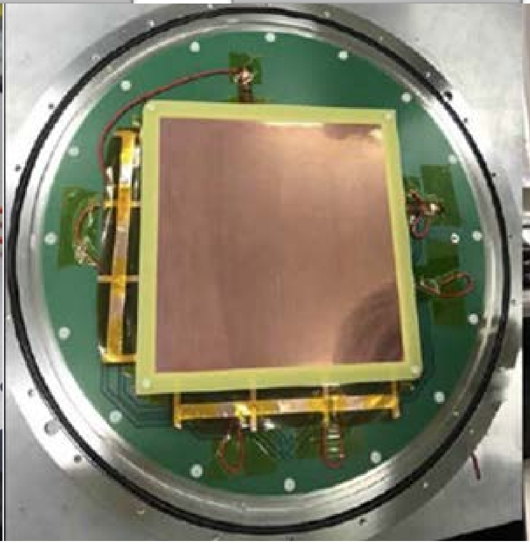
- Study with GEM-MM module
  - New assembled module
  - Active area: 100mm×100mm
  - X-tube ray and 55Fe source
  - Bulk-Micromegas assembled from Saclay
  - Standard GEM from CERN
  - Avalanche gap of MM:128μm
  - Transfer gap: 2mm
  - Drift length:2mm~200mm
  - pA current meter: Keithley 6517B
  -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



CEPC CDR vol. 2, arXiv: 1811.10545

50×50mm^2 2015-2016 → 100×100mm^2 2017-2018 → 200×200mm^2 2019-2020

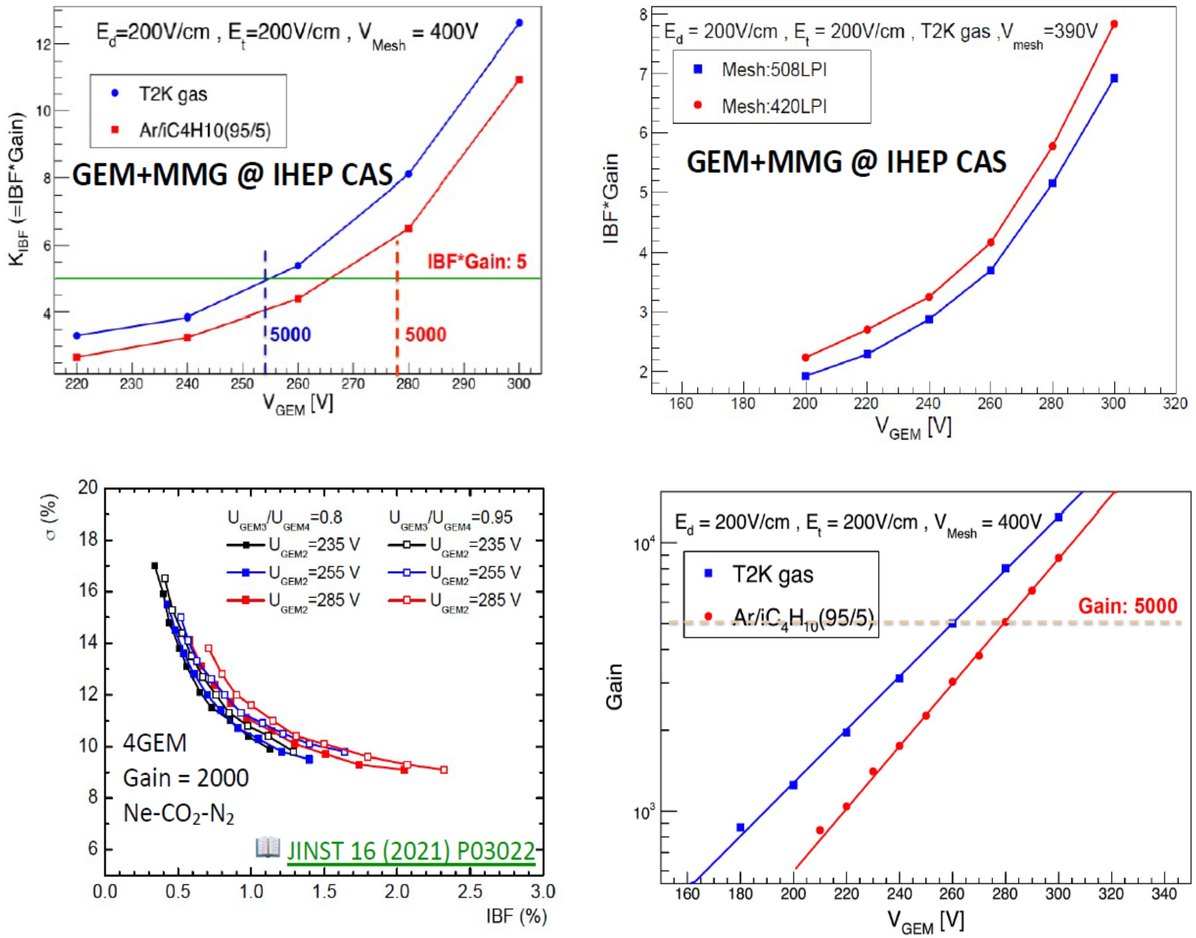




GEM-MM detector cathode

TPC detector module@IHEP

- Study with GEM-MM module
  - CEPC: keep IBF × Gain ≤ 5@Gain/5000
  - When MPGD gas gain<2000, IBF × Gain ≤ 1
  - Studies with hybrid GEM+MM detectors
  - sPHENIX R&D with 2GEM+MMG
  - USTC with DMM
- To be optimized:
  - Optimize IBF together with energy resolution/Gain
  - Gas mixture
  - Magnetic field (influence on IBF)
  - Distortion corrections



GEM-MM detector

Ongoing: Amplification structure R&D

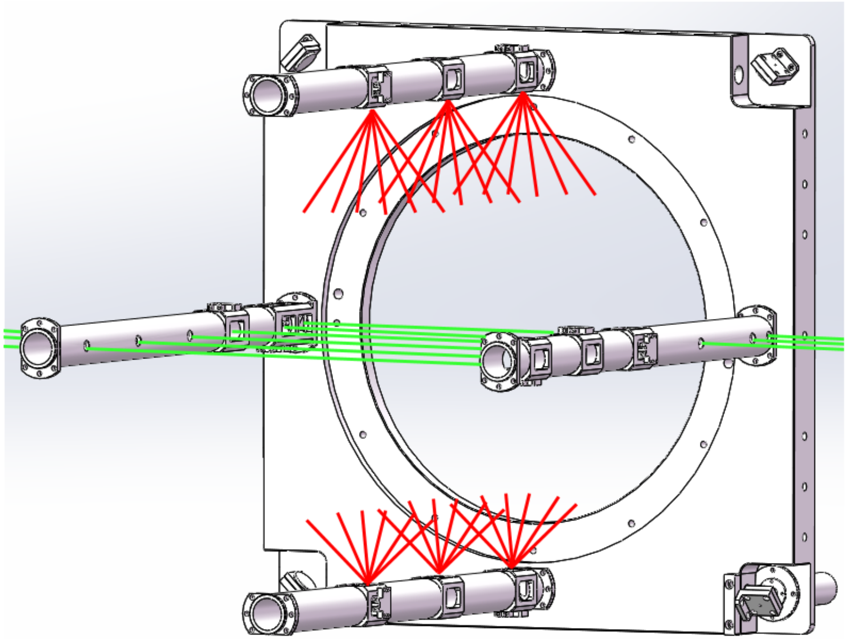
Pixel TPC (double mesh?)	Triple or double GEMs	Resistive Micromegas	GEM+ Micromegas	Double meshes Micromegas
IHEP, Nikehf	KEK, DESY	Saclay	IHEP	USTC 📖 NIM A 976 (2020) 164282 (also 📖 NIM A 623 (2010) 94)
Pad size: 55um-150um square	Pad size: 1mm×6mm	Pad size: 1mm×6mm	Pad size: 1mm×6mm	Pad size: 1mm×6mm (If resistive layer)
Advantage for TPC: Low gain: 2000 IBF×Gain: 1-2	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

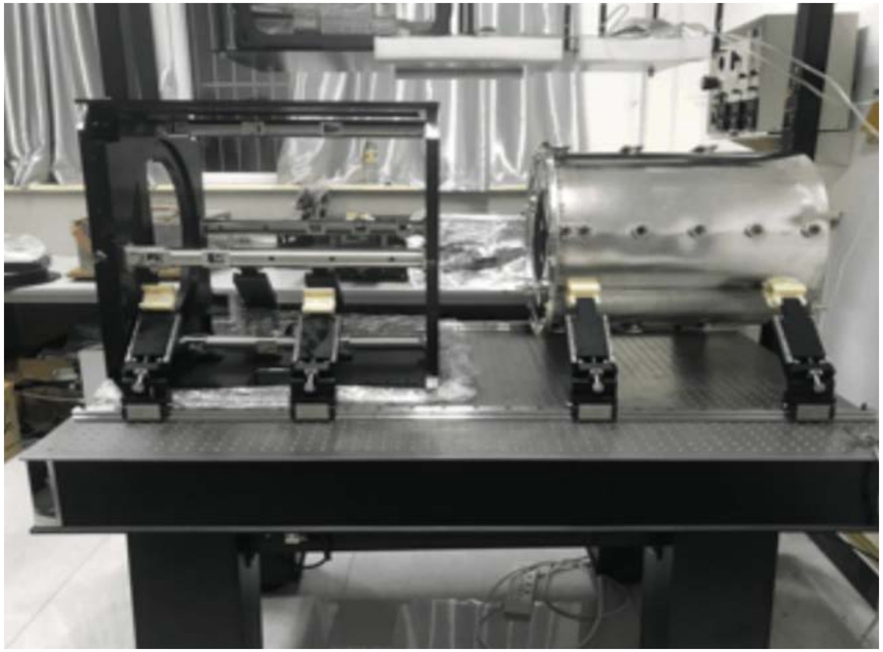
Status of TPC prototype@IHEP

- Data taking and more analysis on going
- **Commissioning:** Huirong Qi, Zhiyang Yuan, Yue Chang, Yiming Cai, Yulan Li, Zhi Deng
- **Data taking:** the same, plus: Hongyu Zhang, Ye Wu

TPC prototype sketch

- Main parameters
  - Same test parameters in CEPC
    - Drift field=200V/cm
    - Relative gain: ≥2000
    - Readout pad(anode) is designed to 0V (Ground)
    - TPC detector system: Fieldcage+ Pads readout
    - Working mixture gas:
      - $Ar/CF_4/iC_4H_{10}$=95/3/2
      - Same purity
  - Specific prototype parameters
    - Drift length: ~500mm
    - Active area: $200mm^2$
    - Integrated 266nm laser beam
    - MPGD detector as the readout
    - TPC cathode: -10kV
    - Readout Pads: 1280 channels

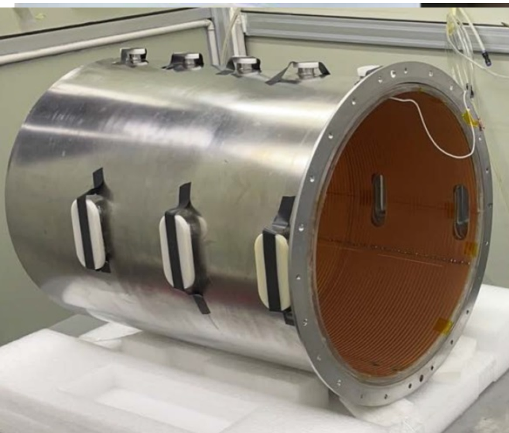
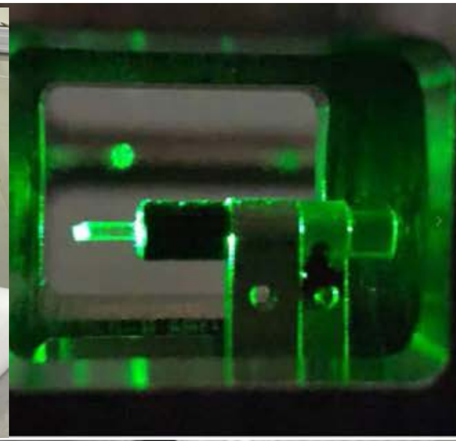
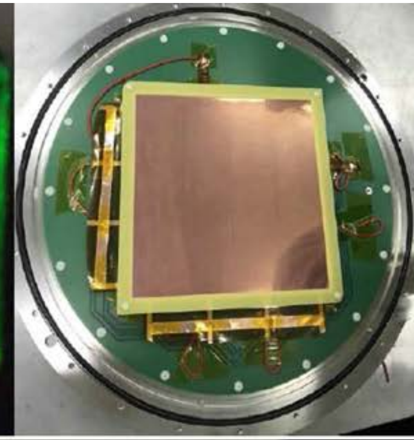
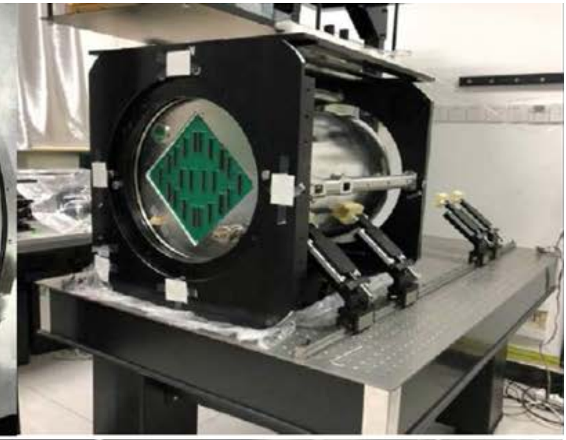
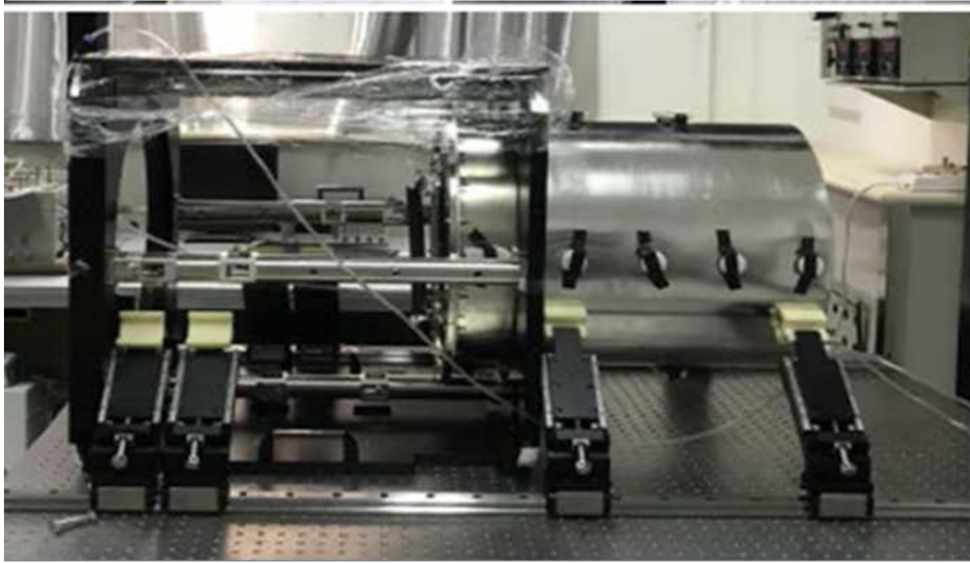




TPC prototype

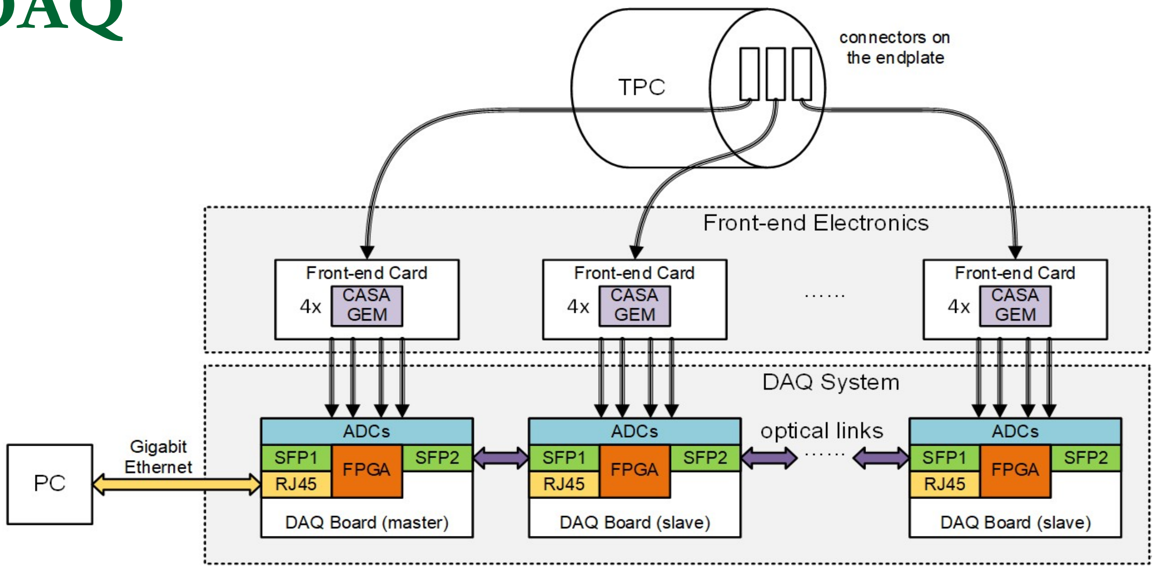
Commission: Chamber/Fieldcage/UV laser/Readout

- GEM detector as the endplate with 200mm^2
- Cylindrical flexible circuit board with 0.15mm thickness
- 500mm drift length with 20000V high voltage
- Integration of the 266nm UV laser tracks in the chamber

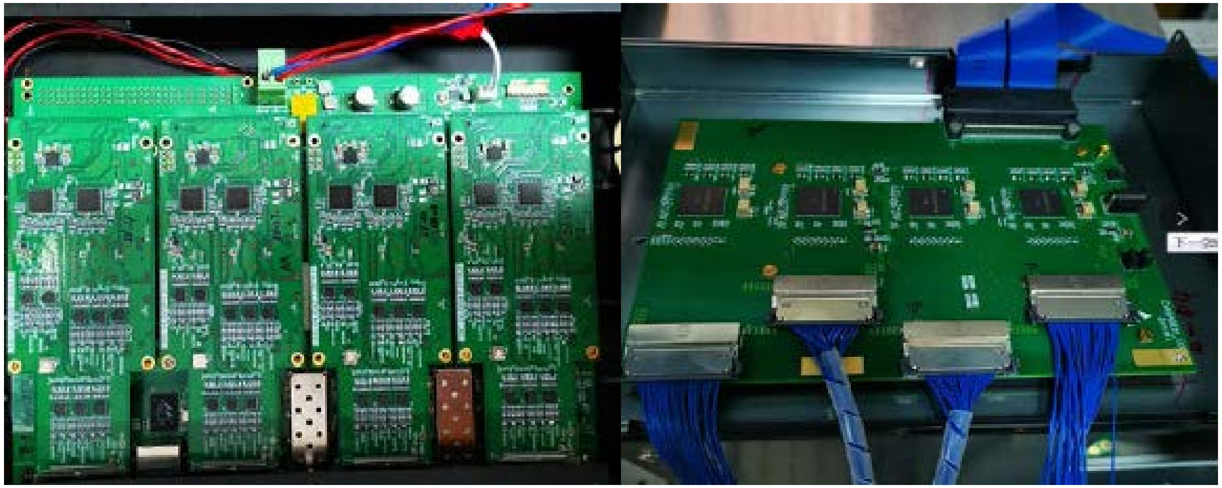







Electronics and DAQ

- Amplifier and FEE
  - CASAGEM chip
  - 16Chs/chip
  - 4chips/Board
  - Gain: 20mV/fC
  - Shape time: 100ns

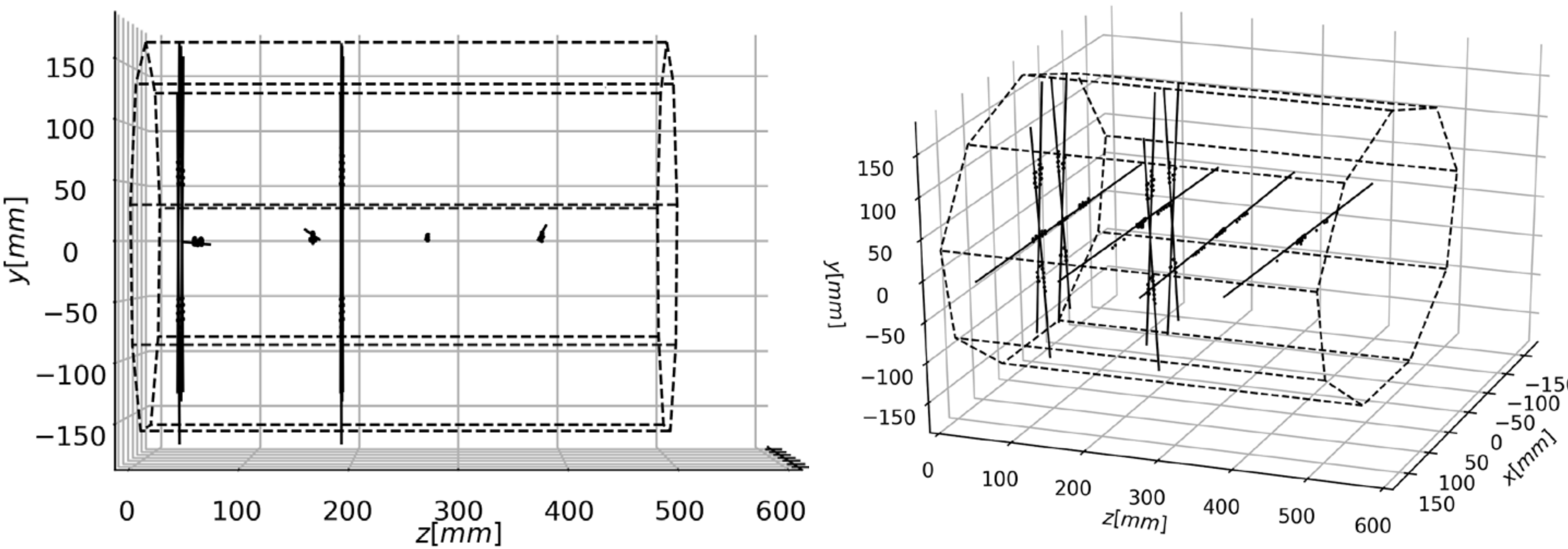


- DAQ
  - FPGA+ADC
  - 4 module/board
  - 64Chs/module
  - Sample: 40MHz
  - 1280chs



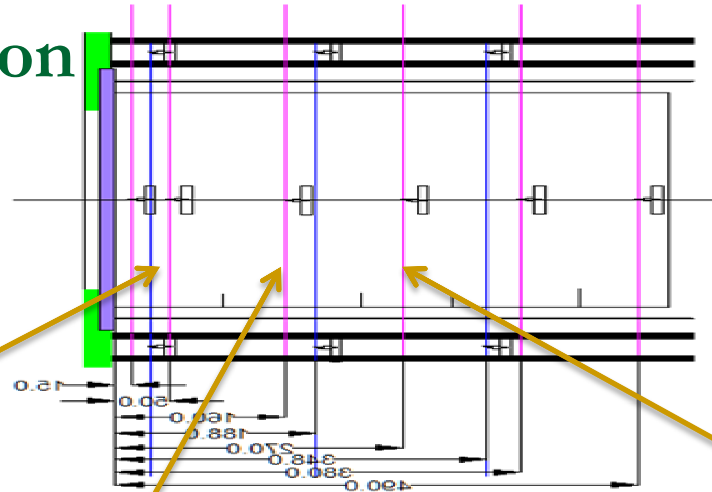
FEE Electronics and DAQ setup photos

Laser tracks in chamber@T2K gas

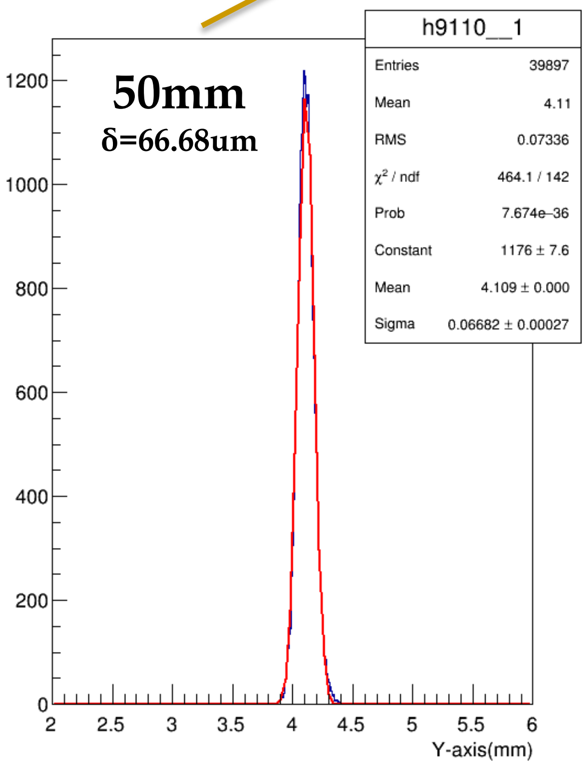


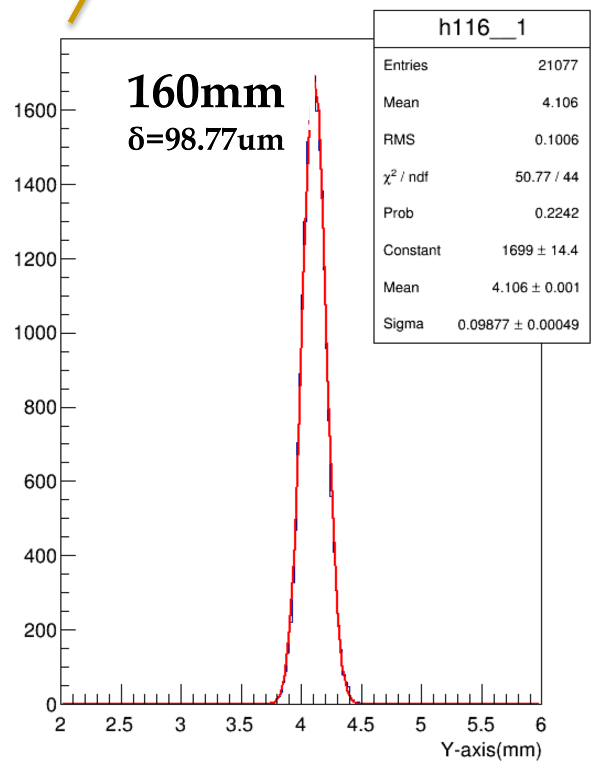
- Same of working gas@T2K, same of high voltage, same of test conditions
- Different of GEMs@ 320V
- Double GEMs without any discharge

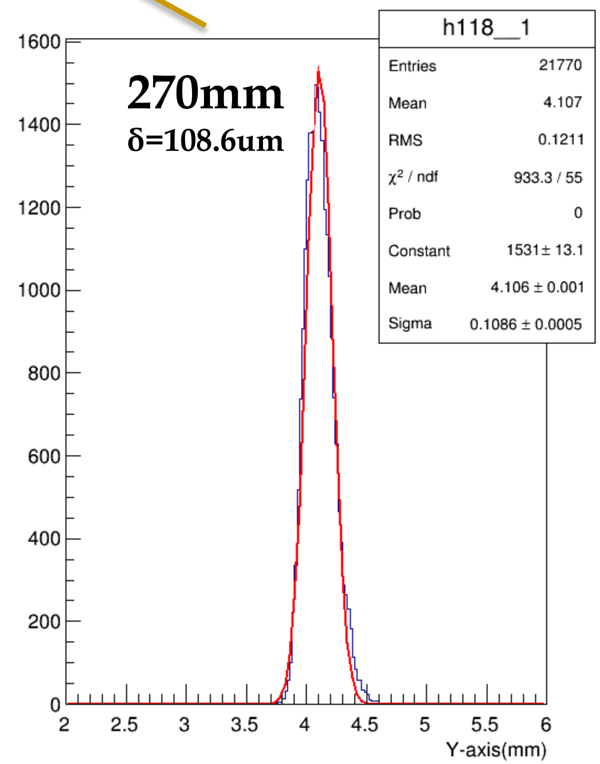
Spatial resolution



N_{eff} of UV laser
in test: ~80



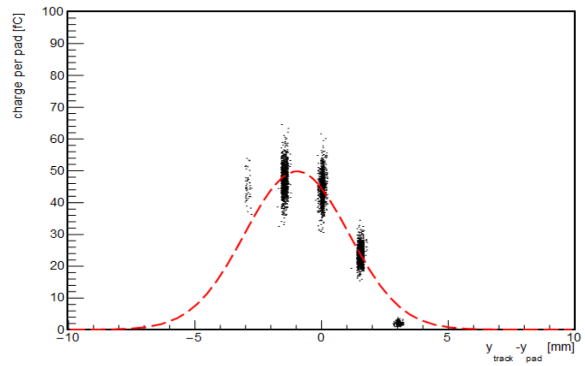


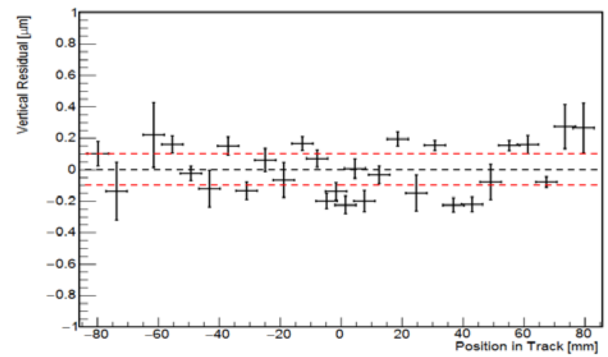


Space resolution at the different drift length

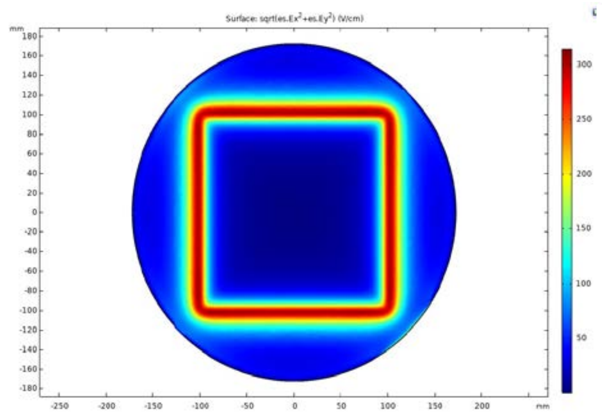
Spatial resolution correction

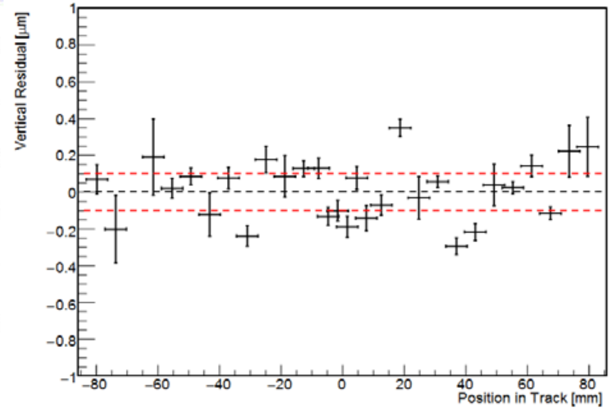
Charge of the readout pads correction





Electric field of the drift length correction





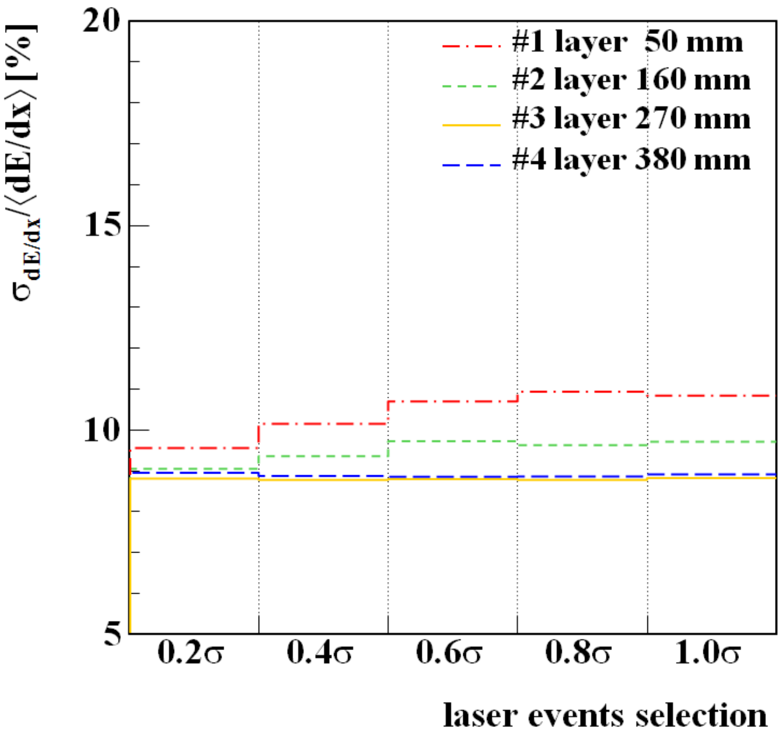
Laser track correction @$180V/cm$ @380mm

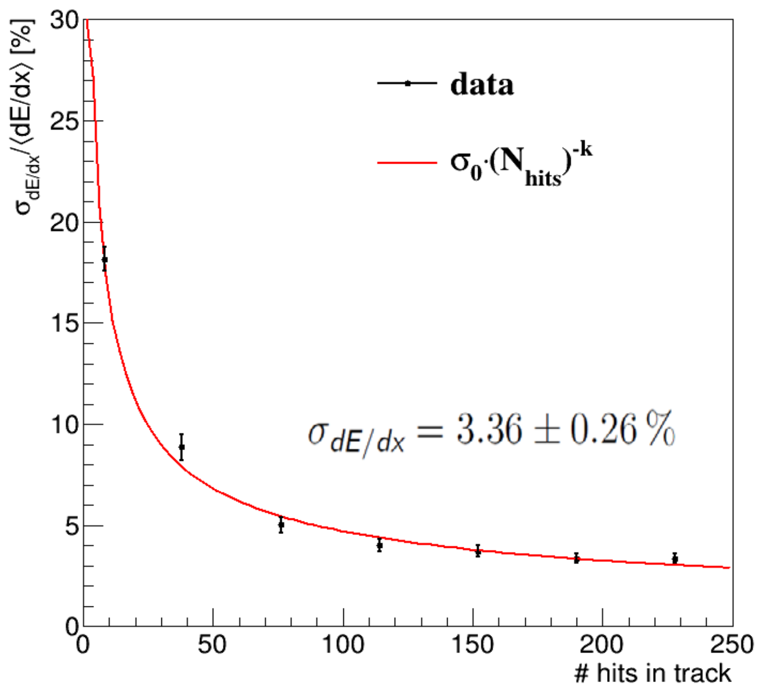
	data w.o	Simulation	+Q corr.	+ Q + E corr.
Spatial resolution (μm)	184.83	$\frac{D_T\sqrt{Z_{Drift}}}{\sqrt{N_{eff}}} = 113.00$	144.60	130.52

Spatial resolution along the drift length with correction

PID analysis using UV laser tracks

- dE/dx resolution achieved with pseudo-tracks of various lengths
- Comparison of simulation and experimental dE/dx
- Pseudo-tracks with 220 layers and dE/dx can reach to $3.36 \pm 0.26\%$





Conclusion:

266nm UV laser can work well when it can be as the online mimic tracks.

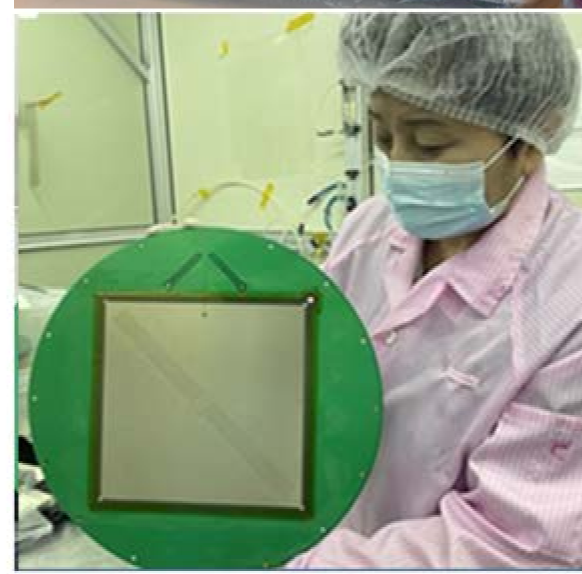
Some related TPC R&D

Goals:

- **Different size of TPC modules production**
- **Low power consumption FEE ASIC chip R&D**
- **Some other readout options for TPC prototype**
- **Collaboration of TPC technology in international LCTPC for e^+e^- collider**

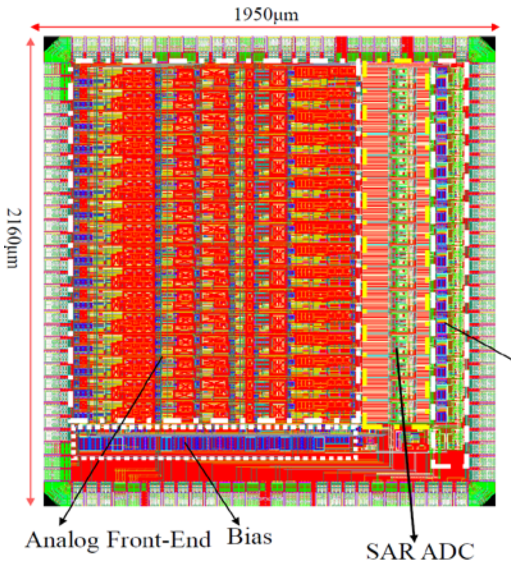
Start of Micromegas detector production in 2021

- >50m^2 yellow light production lab
- Some samples of the detector module successfully were assembled in our lab(200mm^2)
- The different active area of the detector could be prepared, and the maximum size could be more than 1000mm
- The gain test of the detector were fine at T2K/$Ar:CO_2$ mixture gases



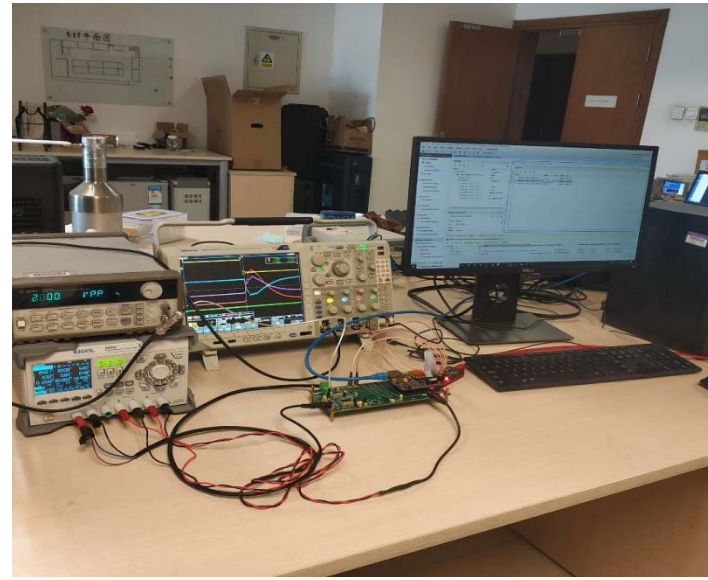
Low power ASIC chip R&D

See Liu Wei's talk



- 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

Layout of ASIC chip



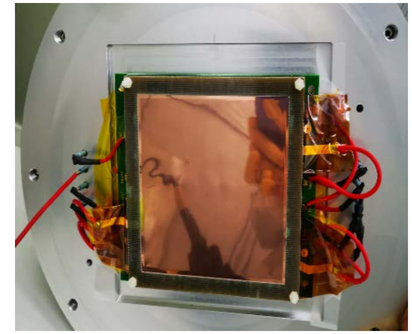
ASIC chip for TPC readout have been developed

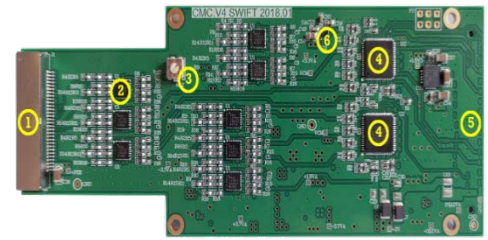
- The power consumption is 2.33 mW/channel
  - P_{AFE} = 1.43 mW/channel
  - P_{ADC} = 0.9 mW/channel @ 40M/s
- ENC =852e @Cm = 2pF, gain =10 mV/fC and can be reduced to 474e using digital trapezoidal filter

Test of the signals

New electronics commissioning

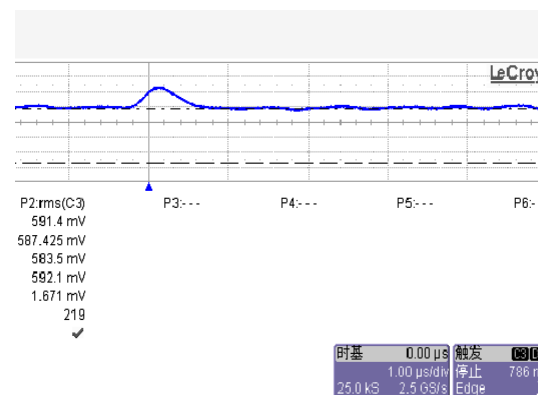
- A 16 channels low power consumption readout ASIC chip for TPC readout have been developed
  - The power consumption is 2.33 mW/channel
    - P_{AFE} = 1.43 mW/channel
    - P_{ADC} = 0.9 mW/channel @ 40M/s
  - ENC =852e @Cm = 2pF, gain =10 mV/fC and can be reduced to 474e using digital trapezoidal filter





Detector and ASIC

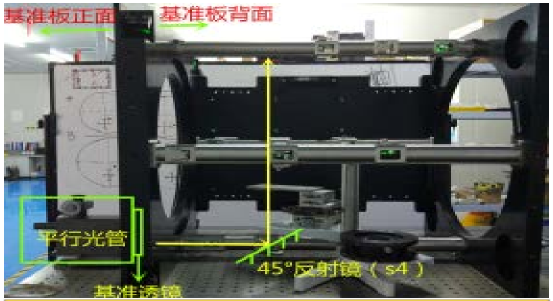
- Future studies
  - More ASIC evaluations: Higher sampling rate, more detailed noise test, test with detectors …
  - Low power digital filter and data compression in FPGA/ASIC
  - 2-phase CO_2 cooling a valid candidate
  - 3D printing complex structures (CEA-Saclay)



Signal of 55Fe

Motivation for the pixelated TPC

See Peter's talk



Pad TPC Prototype
at IHEP 2015-2021

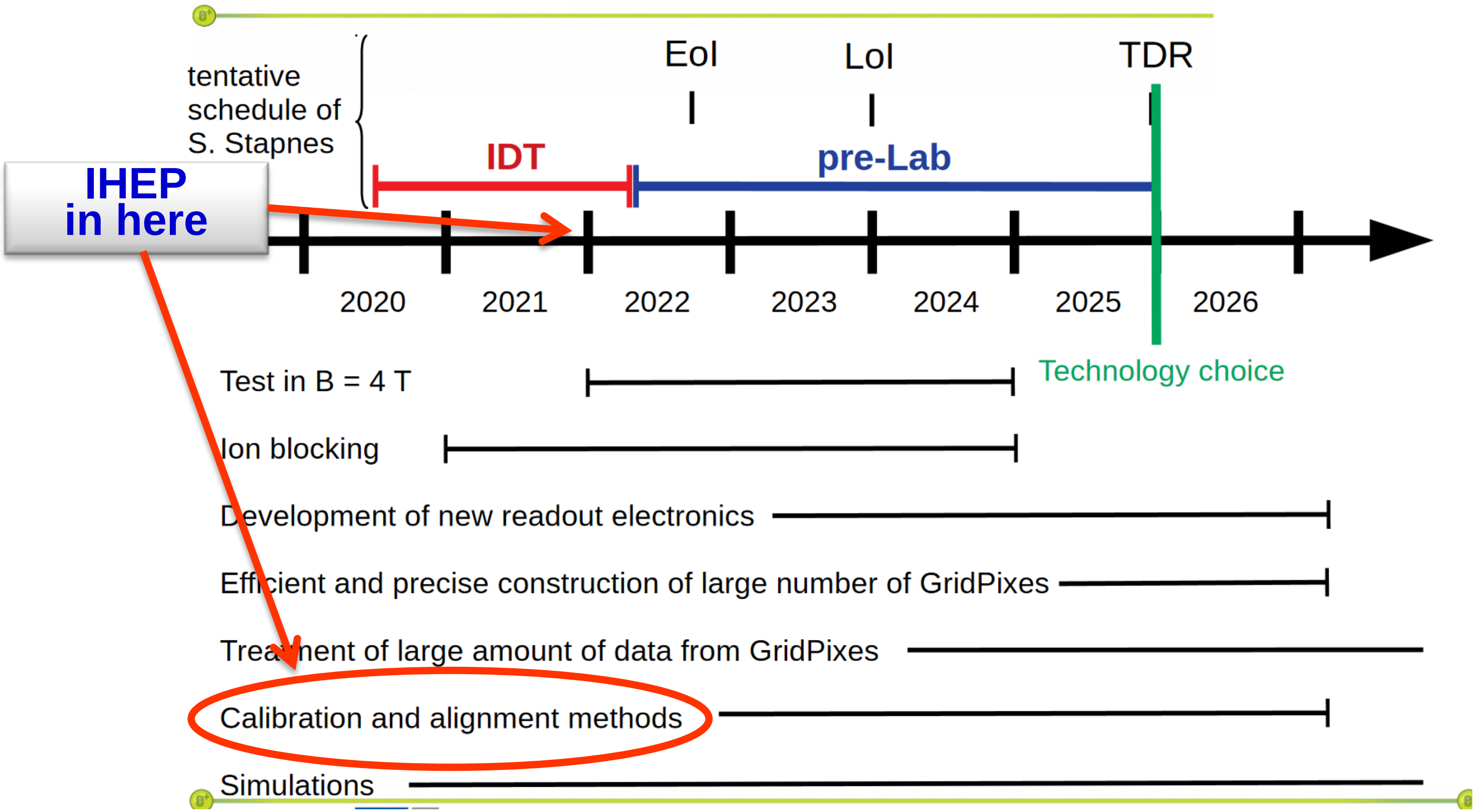
R&D

- Improved dE/dx by cluster counting
- Improved measurement for the low angle tracks
- Improved double track separation
- Much reduced hodoscope effect
  - Near to the endplate
  - Decreased the spatial resolution
- Lower occupancy in the high rate environments
- Fully digital readout

Plans of TPC R&D for e^+e^- collider

- IHEP will continued to involve in TPC prototype test using 266nm UV
- TPC detector assembled and commissioned with the low power consumption ASIC chip
- More contributions will be involve in LCTPC for e^+e^- collider

Timeline e^+e^- collider



Summary

- Some motivations of TPC detector for the circular collider at high luminosity listed.
- Some update results of TPC module have been studies, it can effectively reduce ions at the low gain without the space charge and the discharge.
- Some update results of TPC prototype have been studies, the prototype is working well, and the results indicated that 266nm UV laser beams will be very useful.
- The detector module will assembled and commissioned with the low power consumption ASIC chip.
- More collaboration will be continued for e^+e^- collider.

Thanks for your attention.