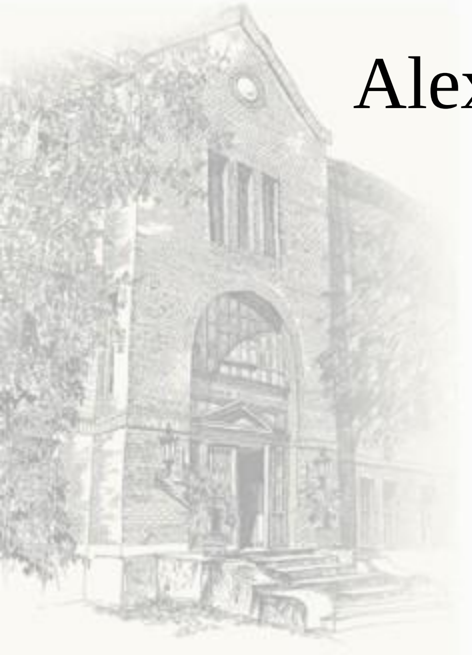
Development of High Precision and Eco-friendly MRPC TOF Detector for EIC (Proposal#14)



Alexandre Camsonne[1],Sanghwa Park[1], Yi Wang[2], Zhenyu Ye[3], Zhihong Ye[2]

10/31/2023

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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清華大學
Tsinghua University

Question 1

- Q1: This proposal and others state that standard non eco-friendly gases "… will soon to be forbidden to be used in all U.S. national labs." Is this documented somewhere to clarify these requirements for the EIC?
- There are already limits for National Labs in term of Green House Gas emission to reduce the carbon footprint

Question 1

- Federal Executive Order (EO) 14057.
- Sec. 102. Government-wide Goals.

(iv) a 65 percent reduction in scope 1 and 2 greenhouse gas emissions, as defined by the Federal Greenhouse Gas Accounting and Reporting Guidance, from Federal operations by 2030 from 2008 levels;

- Sec. 202. Reducing Agency Greenhouse Gas Emissions. Each agency shall reduce its scope 1, 2, and 3 greenhouse gas emissions, as defined by the Federal Greenhouse Gas Accounting and Reporting Guidance, by setting and meeting targets for fiscal year 2030 measured from a fiscal year 2008 baseline.

Question 1

- Sec. 205. Achieving Net-Zero Emissions Buildings, Campuses, and Installations.

(a) Each agency shall achieve net-zero emissions across its portfolio of buildings, campuses, and installations by 2045 and reduce greenhouse gas emissions by 50 percent from buildings, campuses, and installations by 2032 from 2008 levels, prioritizing improvement of energy efficiency and the elimination of onsite fossil fuel use.

(b) To prioritize reductions in scope 1 greenhouse gas emissions, as defined by the Federal Greenhouse Gas Accounting and Reporting Guidance, agencies should use the Federal building performance standards issued pursuant to section 510 of this order.

(c) To reduce scope 1 and 2 greenhouse gas emissions, as defined by the Federal Greenhouse Gas Accounting and Reporting Guidance, to achieve net-zero emissions buildings, agencies shall:

(i) pursue building electrification strategies in conjunction with carbon pollution-free energy use, deep-energy retrofits, whole-building commissioning, energy and water conservation measures, and space reduction and consolidation;

(ii) design new construction and modernization projects greater than 25,000 gross square feet to be net-zero emissions by 2030;

(iii) implement CEQ’s Guiding Principles for Sustainable Federal Buildings in building design, construction, and operation of all new Federal buildings and renovated existing buildings; and

(iv) use performance contracting, in accordance with the provisions of section 1002 of the Energy Act of 2020 (Public Law 116-133, division Z), to improve efficiency and resilience of Federal facilities, deploy clean and innovative technologies, and reduce greenhouse gas emissions from building operations.

- Sec. 302. Supplier Emissions Tracking. The Administrator of GSA shall track disclosure of greenhouse gas emissions, emissions reduction targets, climate risk, and other sustainability-related actions by major Federal suppliers, based on information and data collected through supplier disclosure pursuant to the requirements of section 5(b)(i) of Executive Order 14030 of May 20, 2021 (Climate-Related Financial Risk), and shall assist the Chair of CEQ in assessing the results of efforts to reduce Federal supply chain emissions.

Question 2

- Q2 : Previous studies were done with CAEN waveform digitizer DT5742 chip but this proposal describes new SAMPIC or pico-TDC based readout. What are the benefits of these options to justify the development of MRPC with eco-friendly gases?

- Some studies show performance at 20 to 15 ps level electronics with 5 ps or better needed to take full advantage of such performances : requirement for EIC TOF too

Question 2

➢Specs for SAMPIC

		Unit
Technology	AMS CMOS 0.18µm	
Number of channels	16	
Power consumption	180 (1.8V supply)	mW
Discriminator noise	2	mV rms
SCA depth	64	Cells
Sampling Speed	<3-8.4 (10.2 for 8 channels only)	GSPS
Bandwidth	1.6	GHz
Range (Unipolar)	1	V
ADC resolution	8 to 11 (trade-off time/resolution)	bit
SCA noise	<1.3	mV rms
Dynamic range	9.6	Bit rms
Conversion time	0.2-1.6 (8bit-11bit)	µs
Readout time (can be probably be /2)	25 + 6.2/sample	ns
Time precision before correction	15	ps rms
Time precision after timing INL correction	< 5	ps rms

SAMPIC has the required timing resolution

Question 2

- Pico and PicoTDC
- Amplifier Discriminator with Time Over Threshold
- High density TDC with 5 ps timing resolution
- Cheaper cost per channel than full waveform
- Commercial CAEN module and custom Tsinghua available

Question 3

- Previous studies of sMRPC at the Fermilab test beam did not have the required electronics to be successful. If new electronics are being developed for this case, what milestones will be set to ensure the readout is ready in time for the beam tests described in this proposal? Please describe the proposed timeline for the beam tests and the preparation of electronics to meet that timeline
- Electronics available at Tsinghua :
- DRS4
- PicoTDC
- Can already be used with their custom software

Question 3

- A few months planned to integrate within JLab CODA framework for convenience and to be able to handle larger scale number of channels for final beam test later in the year
- Synergy with EIC/ePIC DAQ timing distribution system : other TOF technologies could use readout for beam tests

Timeline

January 2024	February	March	April	May	June
Setup Gas system UIC Ship DRS4 and picoTDC to JLAB and UIC Order SAMPIC	Test electronics with custom software and pulser Start integration with CODA	Start Cosmics UIC With new electronics SAMPIC delivered Cosmics with custom software	Start SAMPIC integration with CODA	Continue Cosmics within CODA framework Develop analysis tools	Take cosmics with SAMPIC, DRS4 and pico TDC in CODA

Timeline

July	August	September	October	November	December
Ship MRPC, Gas system, and electronics To JLab Cosmics At JLab	Cosmics At JLab Installation in Hall A or Hall C	Beam starts Mid September		Preliminary results sMRPC Timing resolution In beam and high background	Beam ends Mid December

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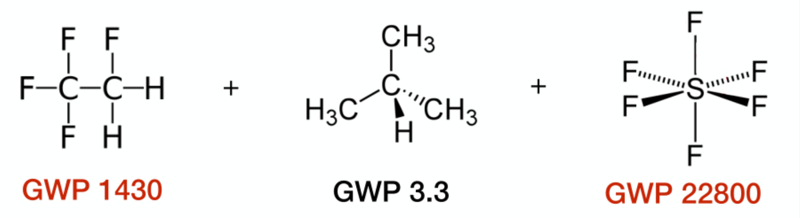
Motivation on eco-gas

Global Warming Potential measures how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide.

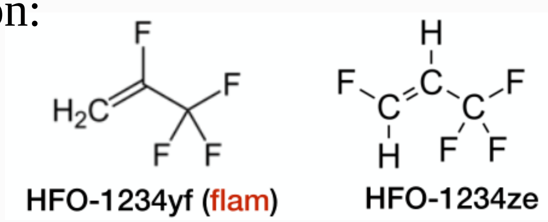


European Union **"F-gas regulation"**:
- **Limiting the total amount** of F-gases that can be sold in the EU
- **Banning the use of F-gases** in many new types of equipment.
- **Preventing emissions** of F-gases from existing equipment.

Much uncertainty about the **price and availability** in the future

Eco-gas replacements:

-for Freon:



GWP 4 6

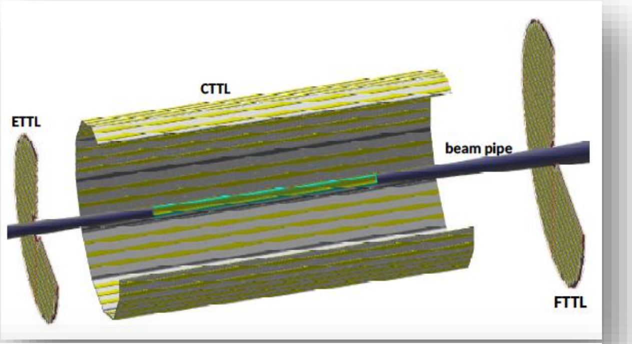
* One more carbon with a double bond, ideal substitute as refrigerant. Unknown about the performance of ionization.

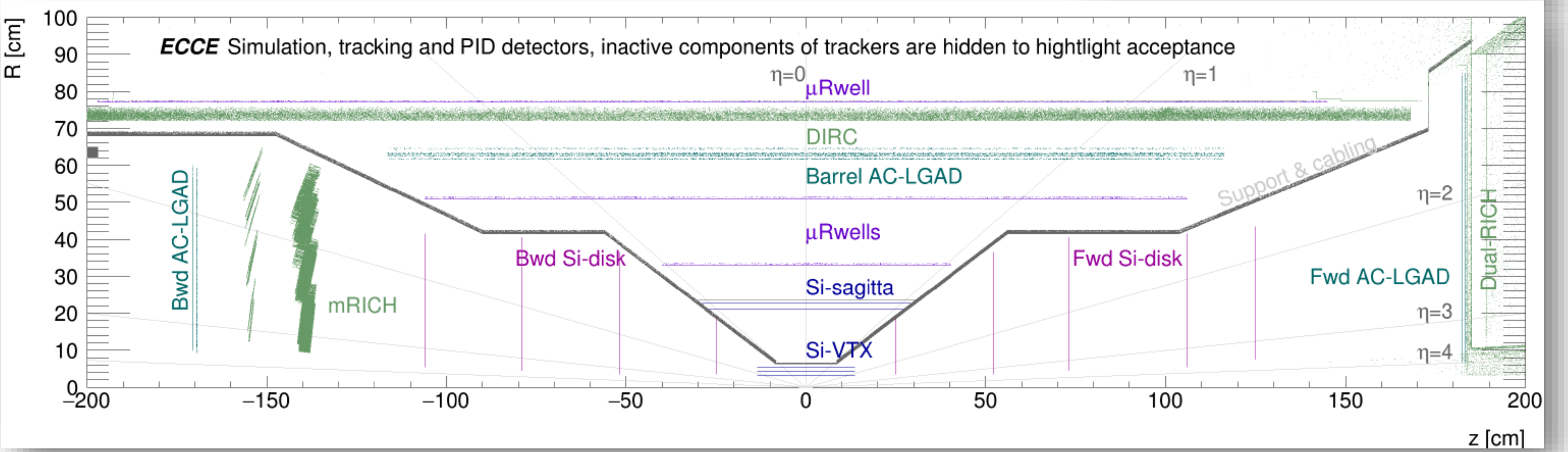
-Eco-gas mixtures:

Relevant test should start as soon as possible.

TOF on EIC

- ➢ AC-LGAD as the TOF for ePIC
  - ❑ Goals: 25ps time + 30um spatial resolutions
  - ❑ Cost: ~$10M for 10m^2
  - ❑ Still under active R&D (possible risk)



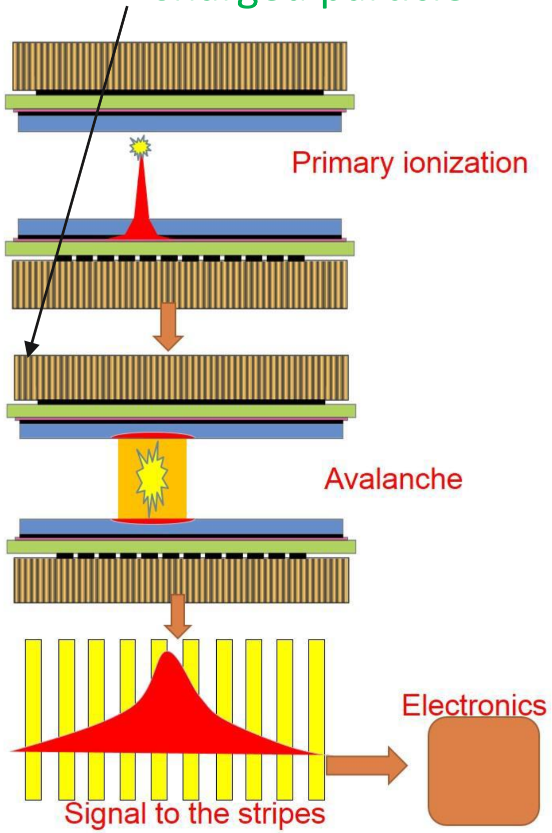


- ❖ Can any places be substituted / complemented?
- ❖ Alternative TOF solution？
- ❖ The second IP detector?
- ❖ High rate / high radiation detector : forward detection

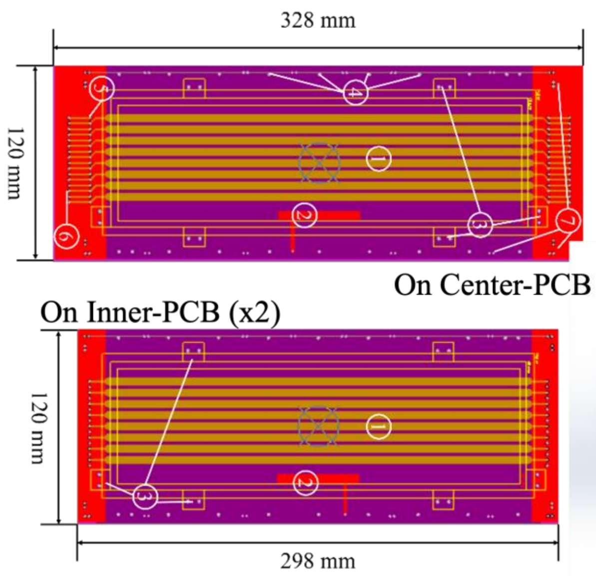
- ▪ Center Detector (most recent setup for ePIC):
  - ~~○ Electron Endcap → ~0.8 m^2 (R~70cm),~~
  - ○ Hadron Endcap → ~0.8 m^2 (R~65cm, ~~2m^2 & R~180cm~~)
  - ○ Barrel→ ~10 m^2 (R~64cm, Z~240cm)

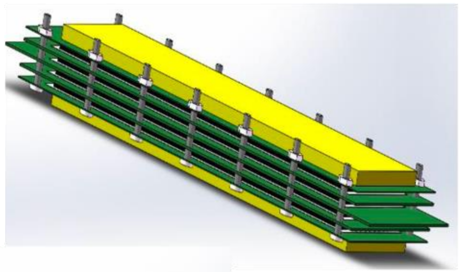
Multi-gap Resistive Plate Chamber (MRPC)

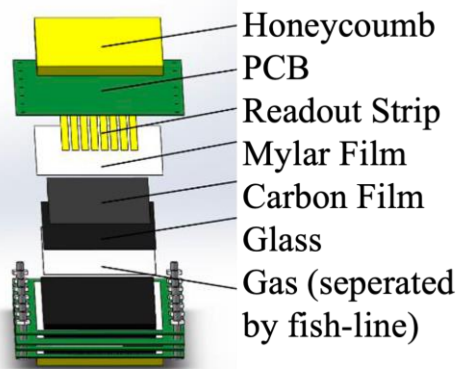
➢ General Princple

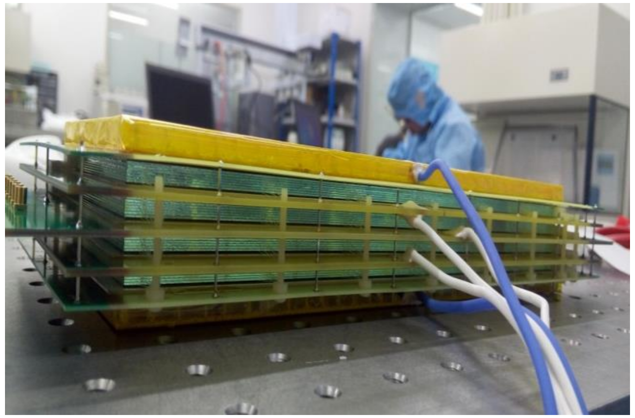


- ❑ Low-resistivity glass plates, Standard gas (95% F134a + 5% iso-butane), HV(~12kV)
- ❑ Good performances:
  time resolution, efficiency, rate capacity (>30kHz/cm^2), radiation-hard, magnet safe
- ❑ Certain spatial resolution (by strip pitch)
- ❑ Low cost, easy manufacturing, large sensitive area (up to 1.0mx0.5m)
- ❑ Used by ALICE, STAR, etc.



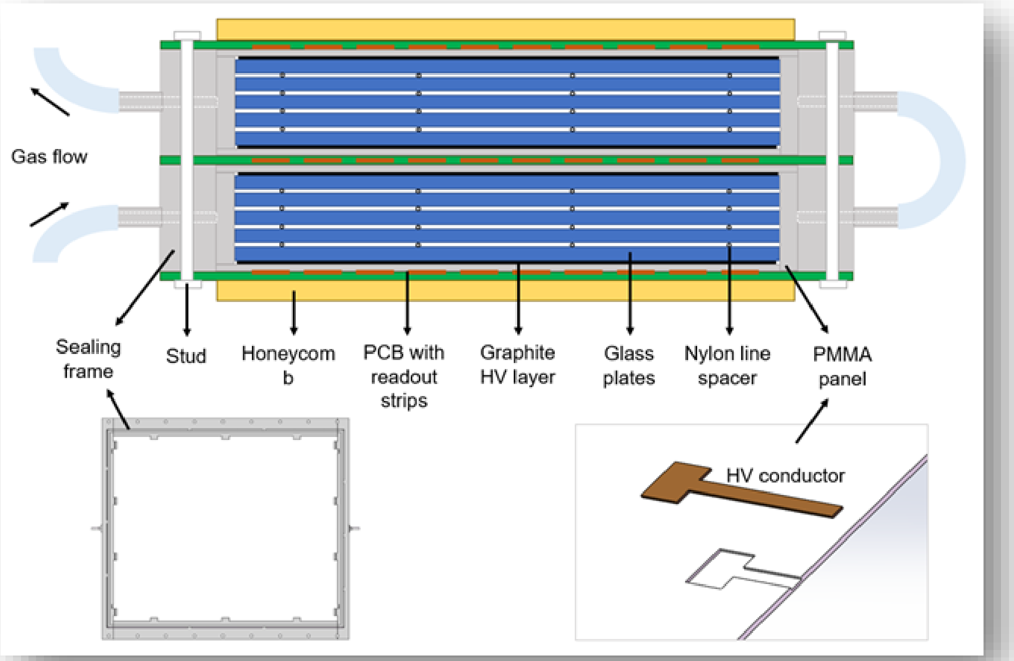




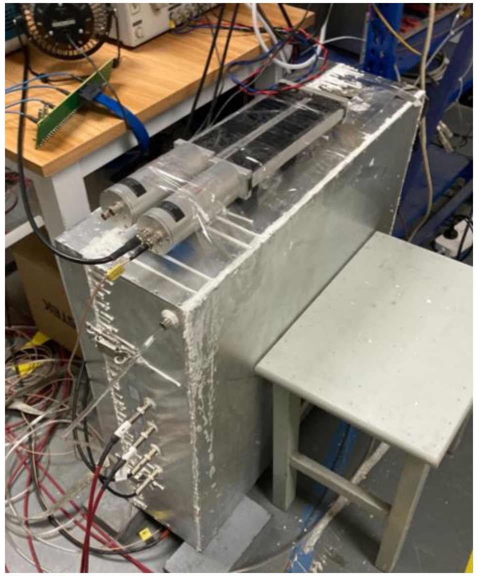


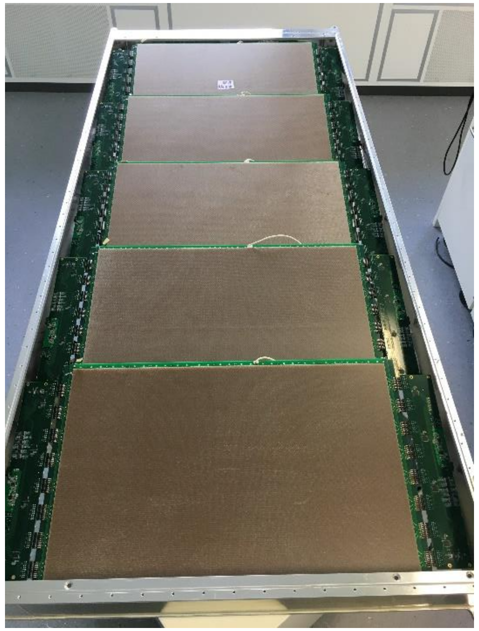
MRPC

- Tsinghua's new Sealed MRPC (sMRPC)
  - Gen3 MRPC with sealed gas → No more boxes!
  - More compact, less radiation length
  - Reduce greenhouse gas emmission (20cc/cm^2/min)

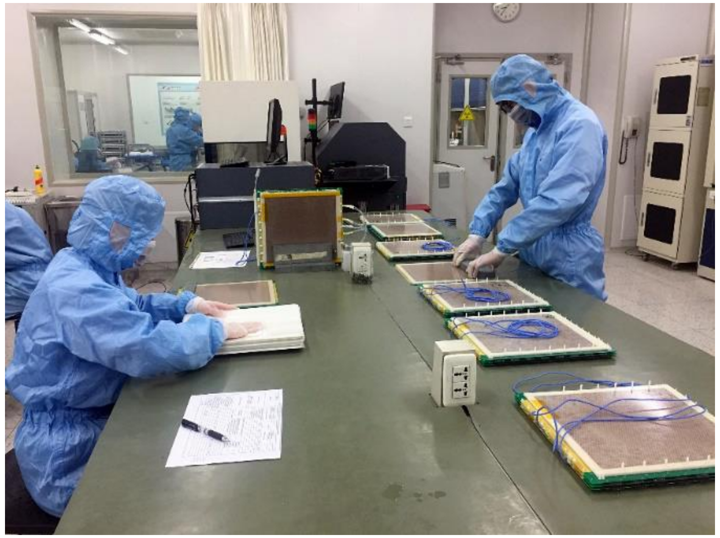


Y. Wang et al 2019 JINST 14 C06015

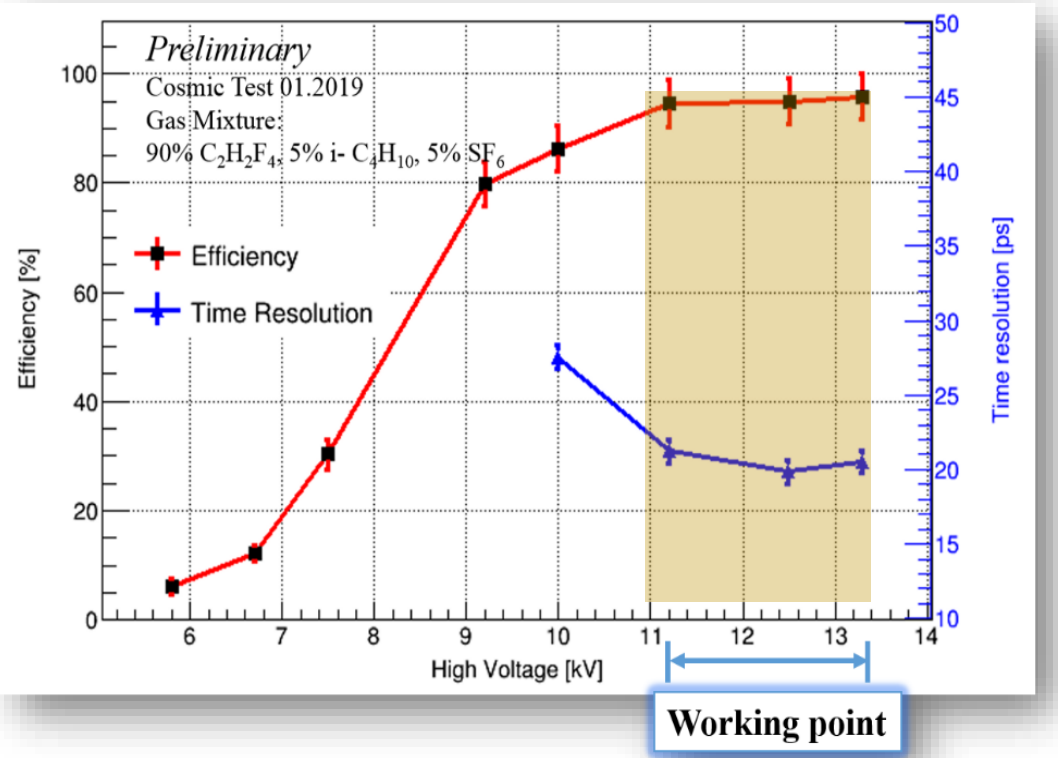


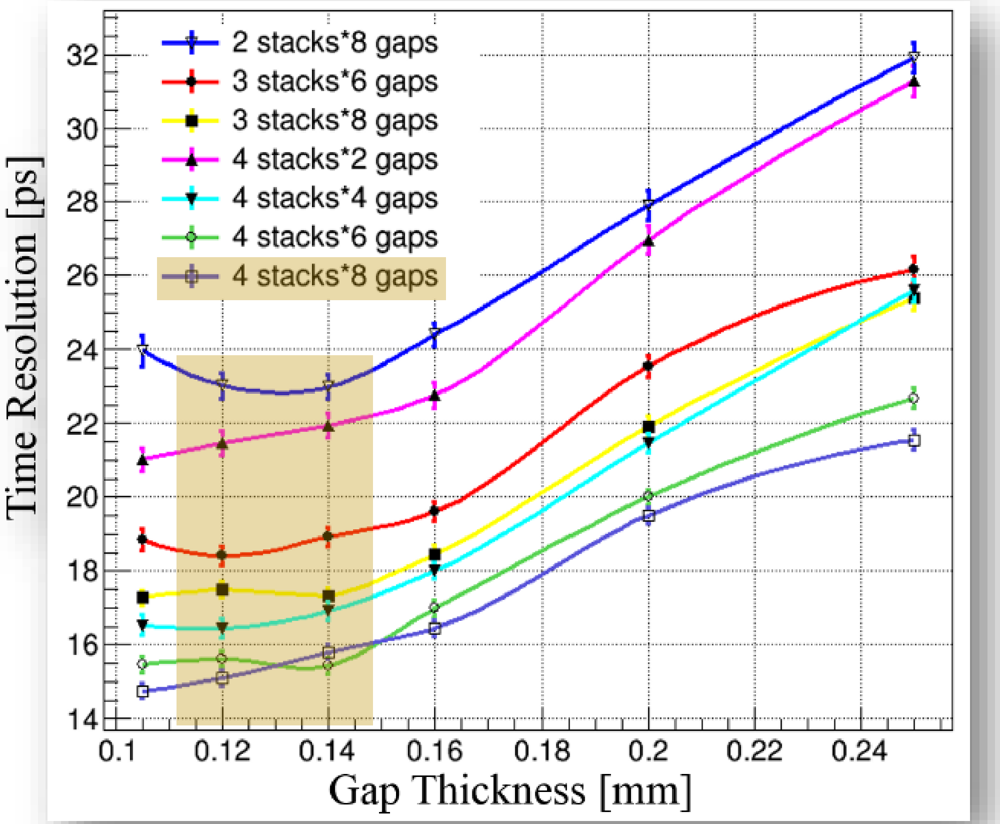


- To be used on CBM, CEE, SoLID, etc.
- Tsinghua's Miyun workshop is continousely conducting mass production of sMRPC for many projects



- Tsinghua's Sealed MRPC (sMRPC)
  - Tunable performance of Gen3 sMRPC
    - ✓ Gaps, layers and HVs can be optimized for different needs
    - ✓ BEST: 32-layers, 400um glass, 128um gap, 12kV



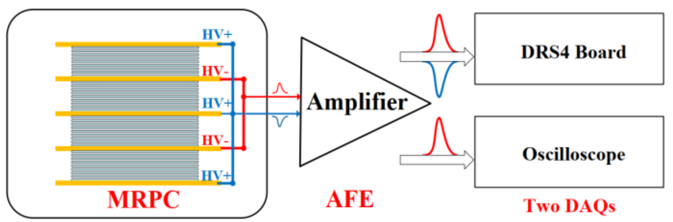


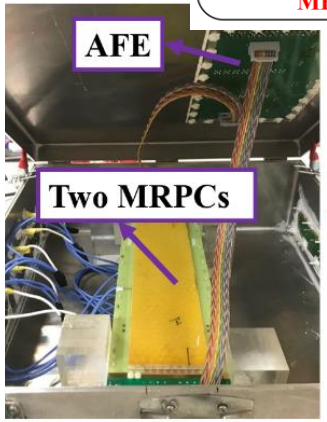
MRPC

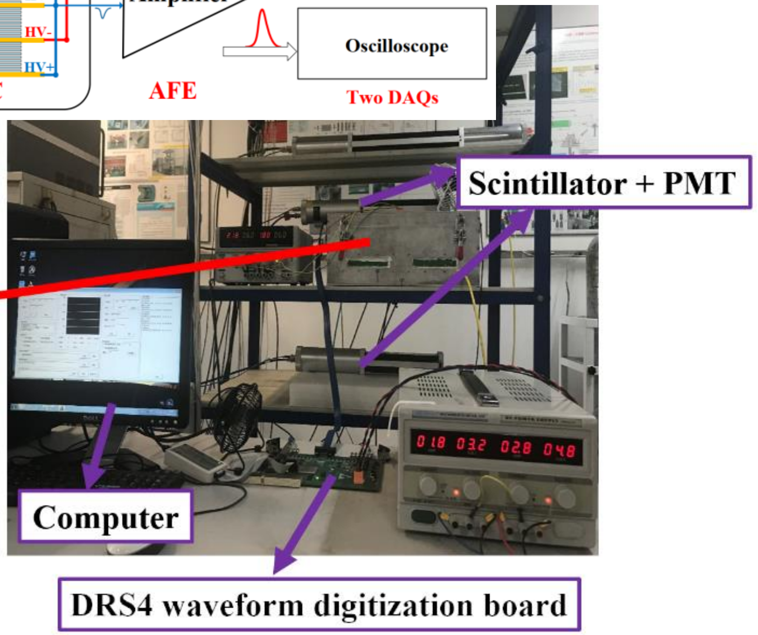
➢ Tsinghua's Sealed MRPC (sMRPC)

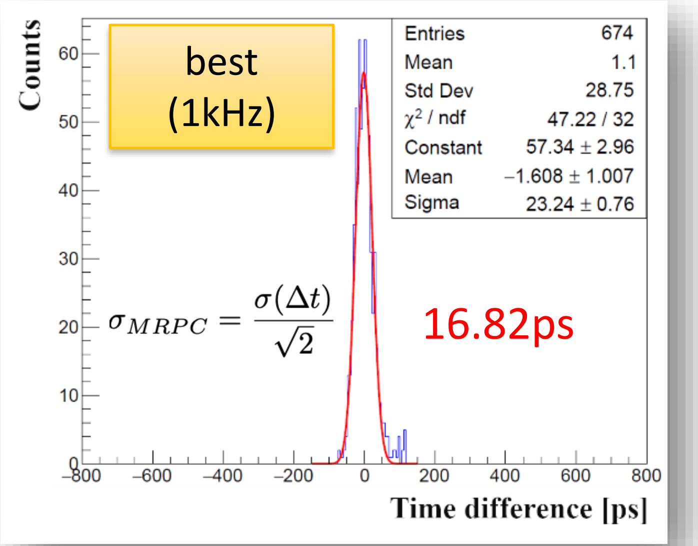
- ❑ Most recent tests: cosmic ray with x-ray background
  - ✓ 32-gaps (4 stacks), 400um thin glasses
  - ✓ 104um gas-gap + waveform-sampling → 20ps & 95% efficiency at 15kHz Y. Yu et al 2020 JINST 15 C01049
  - ✓ 128um gas-gap + ToT method → 20ps at 15kHz

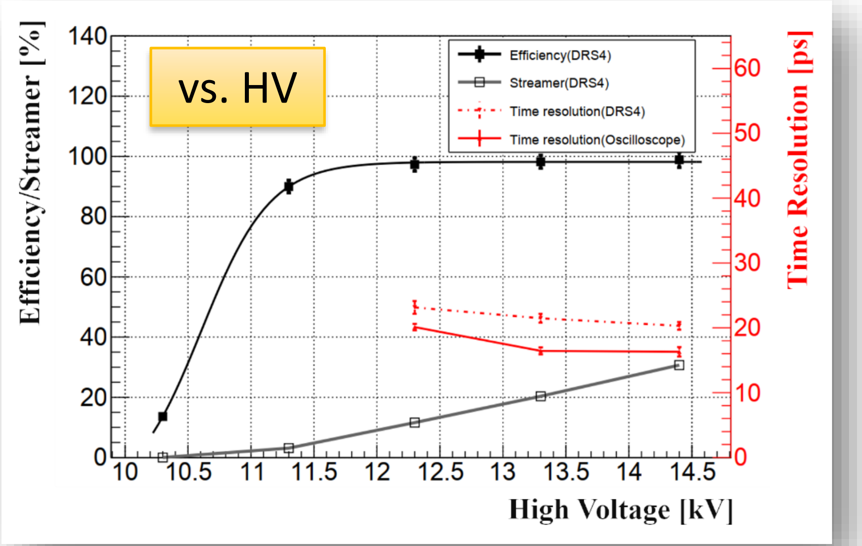
Y. Yu et al 2022 JINST 17 P02005

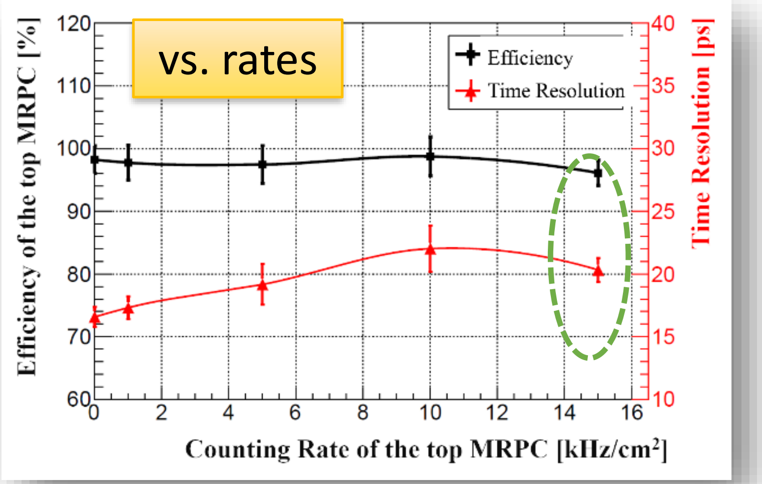






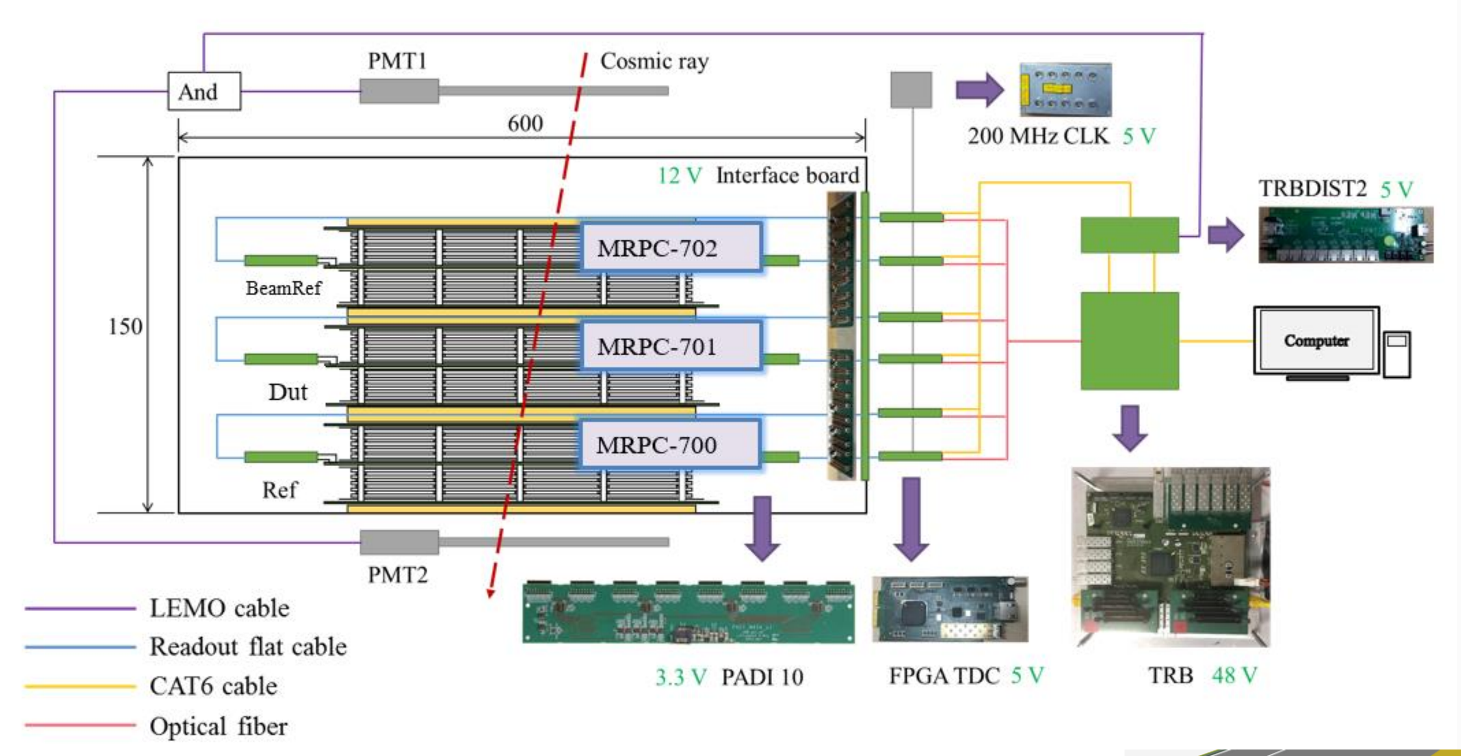




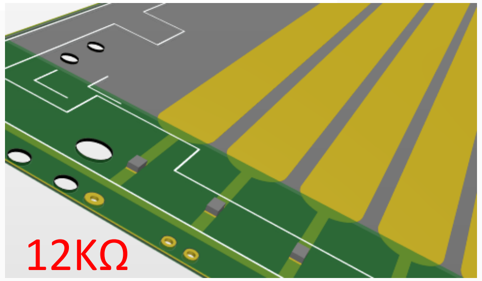


❑ No in-beam test yet

Cosmic Test System



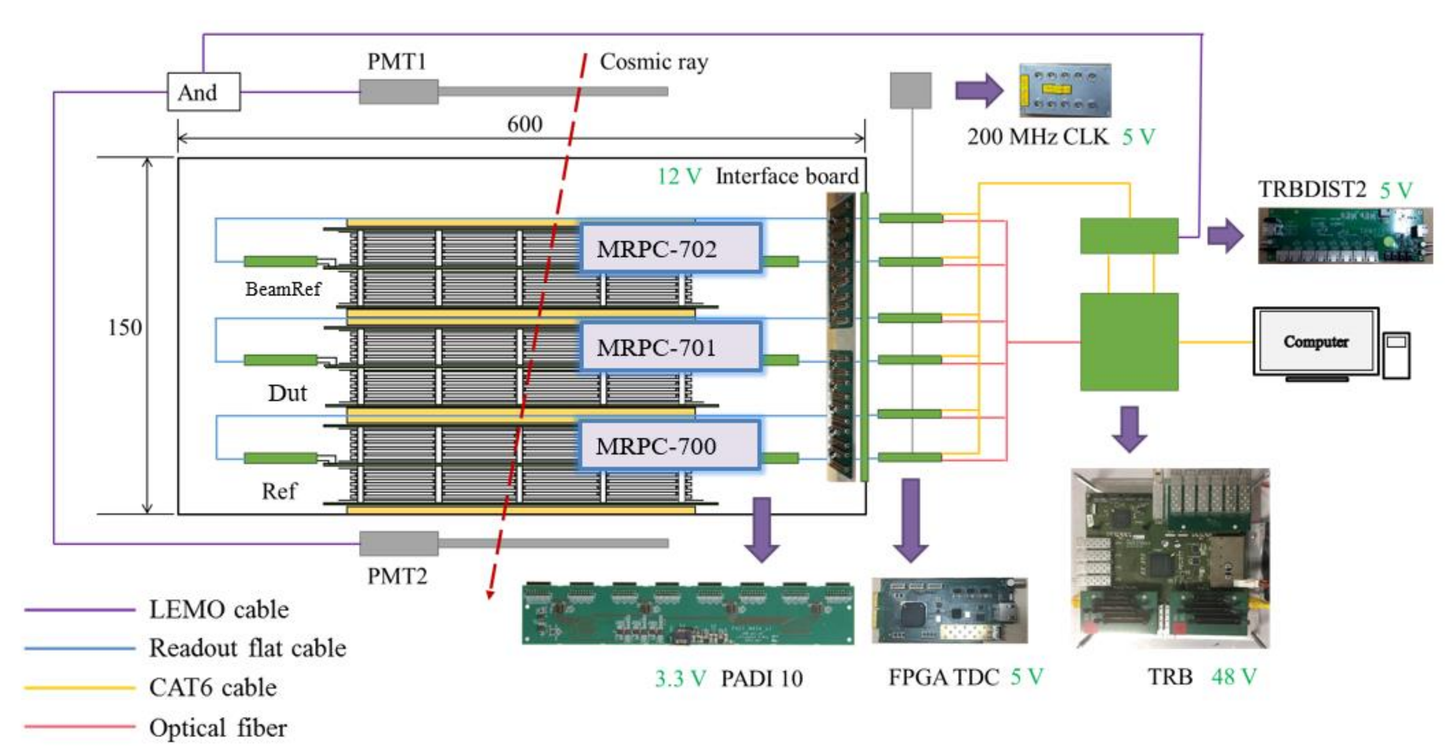
Settings:
700, 702: MRPC3a, 5600V
701: Coupled MRPC, with and without resistors
Gas: Freon/iC4H10/SF6 90/5/5, 70ml/min
Threshold: 300mV
Triggering area: 20cm*5cm



HV board

TSINGHUA UNIVERSITY DEPARTMENT OF PHYSICS

Cosmic Test System (Tsinghua)



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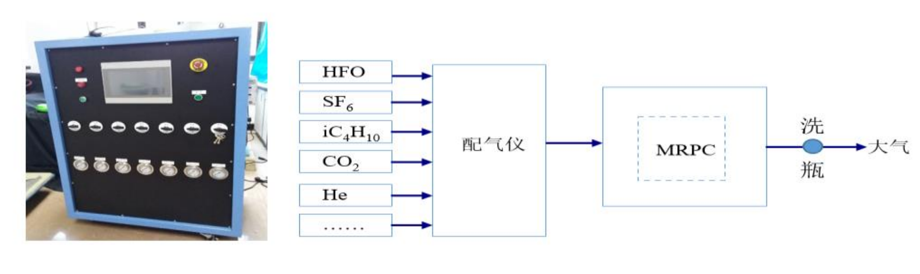


HV board

Eco-gas Test Status

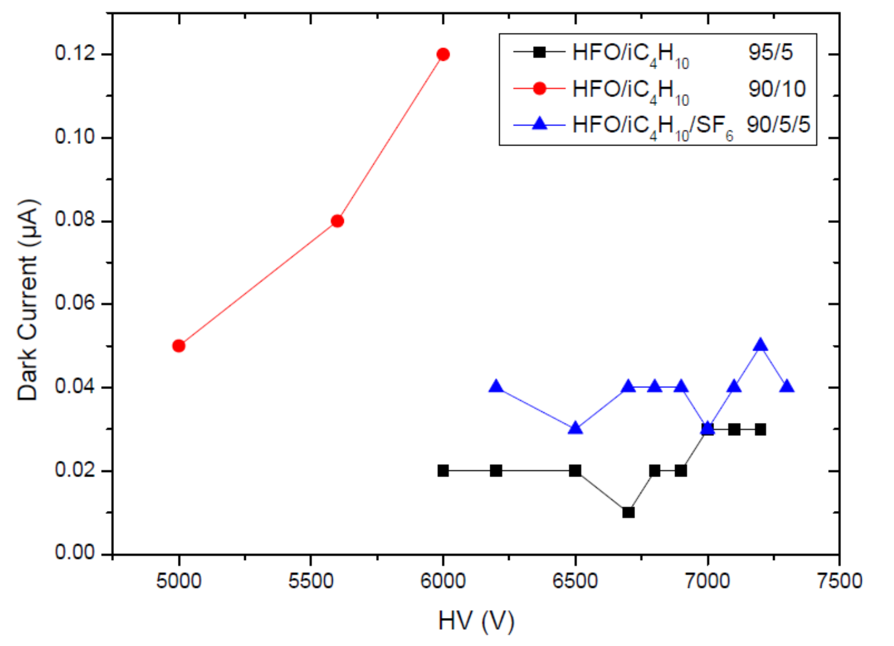
Settings：3 MRPC3a counters
Gas：70ml/min

a. Pure HFO
b. HFO/iC_4H_{10} 95/5
c. HFO/iC_4H_{10} 90/10
d. HFO/iC_4H_{10}/SF_6 90/5/5

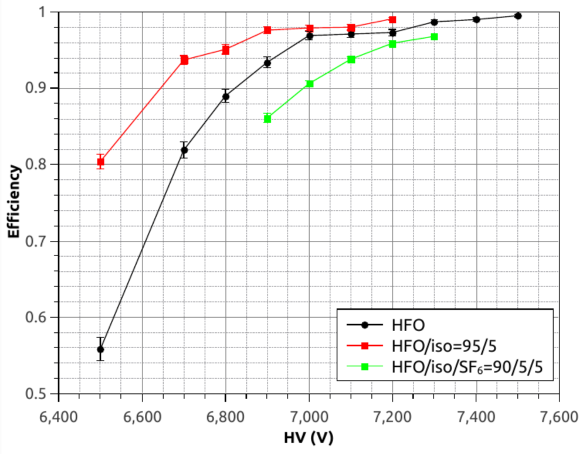
Threshold: 300mV

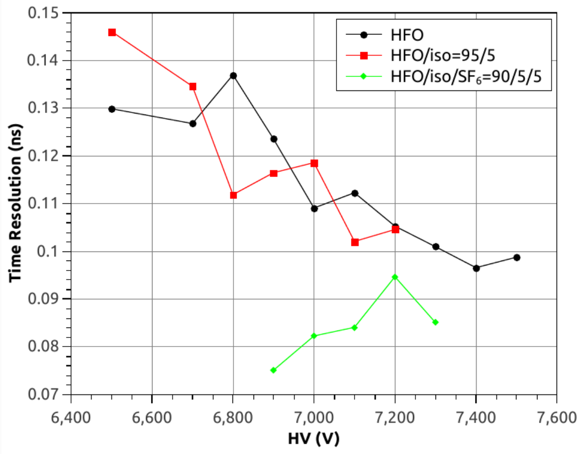
Dark current should be no more than 0.1μA to protect counters.

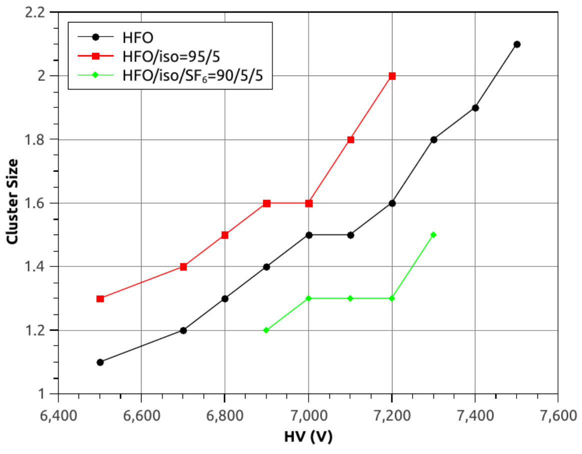
For gas c, fail to apply high enough HV for test. Other gas mixtures can execute the HV scan.



Eco-gas Test Status







At working point：

	HV (V)	Eff	Noise (Hz/cm^2)
HFO	7000	0.959	3.02
HFO/iso 95/5	6900	0.974	1.63
HFO/iso/SF_6 90/5/5	7200	0.962	2.8

MRPC on EIC?

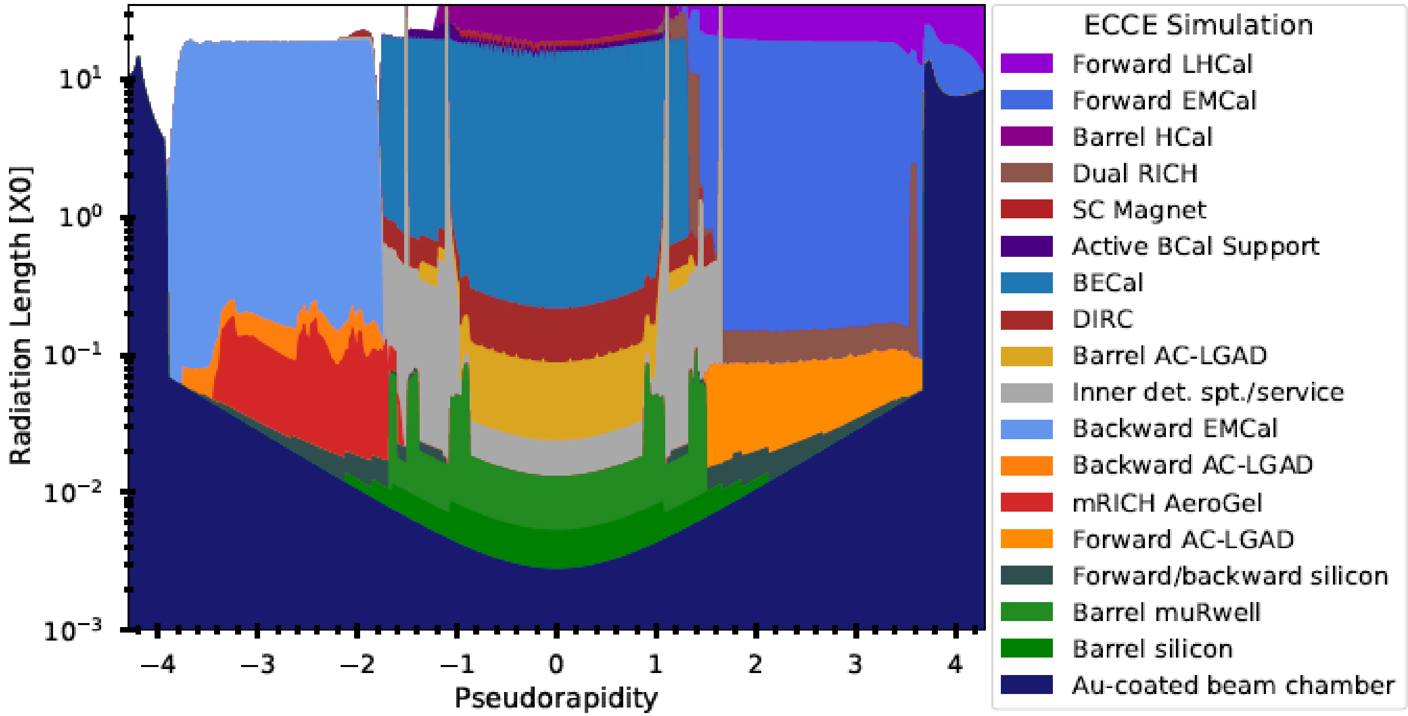
➢ sMRPC's Pros and Cons:

❑ Pros:

- ✓ Proved high-time resolution
- ✓ Radiation-hard, magnetic field safe
- ✓ Cost-effective
- ✓ Mass production
- ✓ No technical risk

❑ Cons:

- Thick (4cm for each plane)
- Large radiation length (32 layers=10% X_0)
- Limited spatial resolution
- Greenhouse gas



❑ Proposing R&D of sMRPC for EIC:

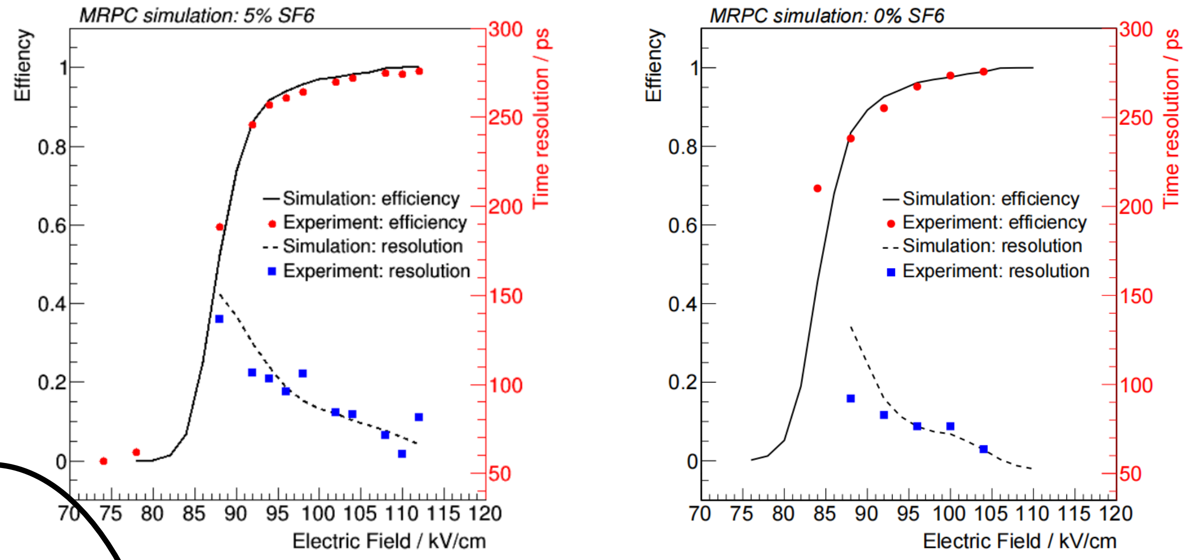
- Reduce thickness with fewer layers (time vs X_0)
- Ecofriendly gas (or gas-recycling system)
- Timing performance in high-energy beam
- Improve spatial resolution w/ finer strip pitch ($$$)

Deliveries#1

F. Wang, JINST, 13(09):P09007, 2018.

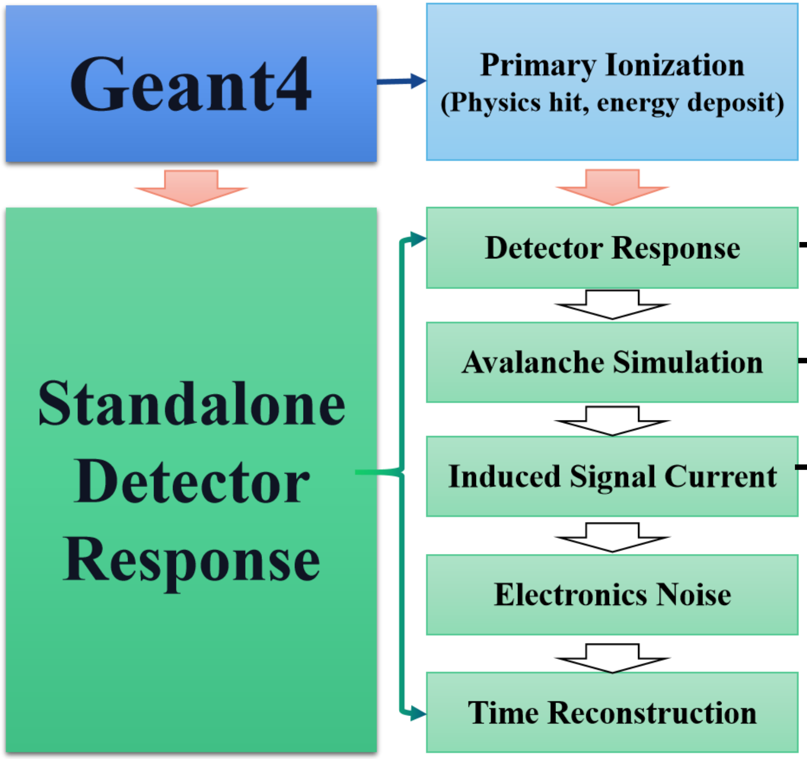
➢ Simulation Framework

- ❑ Tsinghua has developed an efficient MRPC simulation tool



(a) (b)

- ❑ Improvement for future study
  - Eco-friendly gas
  - Reduce gaps (less radiation length)
  - Improve spatial resolution



now	future	goals
Magboltz	→ Betaboltz	→ Better Gas Property Simulation
1D E-Field	→ 3D E-Field	→ Study Space-Charge Effect
Single-Strip	→ Multiple-Strip	→ Strip Optimization

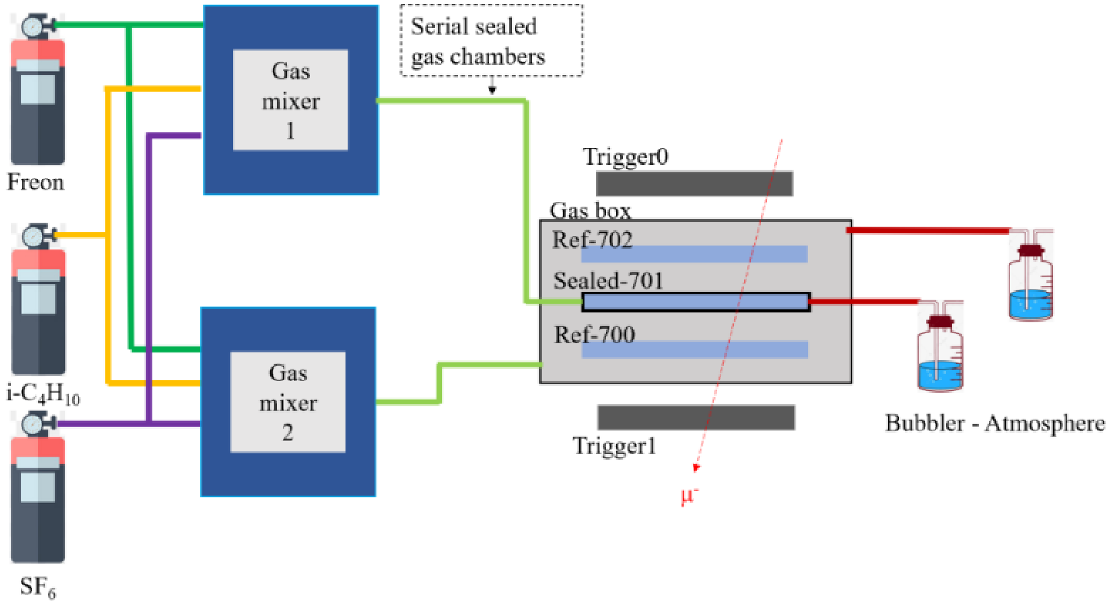
Deliveries#2

➢ Eco-Friendly Gas Replacement

- ❑ Possible replacements of standard gas:
  - ✓ C2H2F4 (R1234ze) + CO2
  - ✓ Argon + CO2
  - ✓ Helium

- ❑ Cons:
  - ▪ Expensive (C2H2F4)
  - ▪ Impact to other detectors (Helium)
  - ▪ Need ultra-high HV

MRPC Standard Gas



- ❑ To-dos:
  - ▪ Simulation with more gas mixtures
  - ▪ Cosmic ray and beam test for actual performance at Tsinghua and UIC

Deliveries#3

- Beam Test
  - Goals:
    - Validate simulation framework and machine-learning method
    - Investigate different eco-friendly gas mixtures
    - Study real performance with high-energy/high-rate background
    - Test out front-end electronics
  - To-dos:
    - UIC local test with cosmic-ray + xray background

      2 planes of 16-layer sMRPC + SAMPIC + picoTDC
    - Tsinghua's local test with cosmic-ray + x-ray background

      2 planes of 32-layer sMRPC + USTC FEE

      + DT5742 (DSR4) and DT5202 (picoTDC)
    - Jlab beam test

      2 planes of 16-layer sMRPC + SAMPIC and NALU + picoTDC

Budget Request

	Personnel	Gas System	Cosmic Test	Beam Test	Sum
Tsinghua	-	-	$10K	$10K	$20K
UIC	$25K	$40K	$20K	$10K	$95K
JLab	-	-	-	$5K	$5K
Total	$25K	$40K	$30K	$25K	$120K

- Tsinghua: (1 FTE Grad student supported by Tsinghua, Travel to U.S.)
- UIC: 0.5 FTE Grad. Student + Gas Circulation-System + Gas Mixtures + HVs + SAMPIC + Trip to Jlab
- JLab: local Gas Circulation-System + Mixtures + Accessories

❖ Additional contribution from Tsinghua

- ✓ 4 low-rate sMRPC with 16 gas-layers (at UIC now)
- ✓ 2 high-rate sMRPC with 32 gas-layers (ship soon)
- ✓ 2 picoTDC modules (128 channels)
- ✓ DT5742 (DSR4)
- ✓ USTC FEE

Detailed budget full funding

Tsinghua University	Travel	$20K
UIC	0.5 FTE student	$25K
UIC	Gas system	$30K
UIC	Gas supplies	$10K
UIC	HV supply	$10K
UIC	SAMPIC×2	$10K
UIC	Travel	$10K
JLAB	Gas supplies	$5K
Total		$120K

80 % budget scenario Tsinghua no trip to U.S.

UIC	Travel	$10K
UIC	0.5 FTE student	$25K
UIC	Gas system and gas	$40K
UIC	HV supply	$10K
UIC	SAMPIC	$5K
JLAB	Gas supplies	$5K
Total		$95K

60% budget scenario No beam tests

UIC	0.3 FTE student	$15K
UIC	Gas system and gas	$40K
UIC	HV supply	$10K
UIC	SAMPIC×1	$5K
Total		$70K

Summary

- MRPC is a good candidate of TOF detectors for modern particle experiments (SoLID, EIC)
  - ✓ Mature technology, high-performance, low-cost
  - ✓ A good alternative TOF option for EIC
- Tsinghua's new sealed MRPC (20ps at 15kHz/cm^2, cosmic ray + Xray) meets EIC-TOF requirements

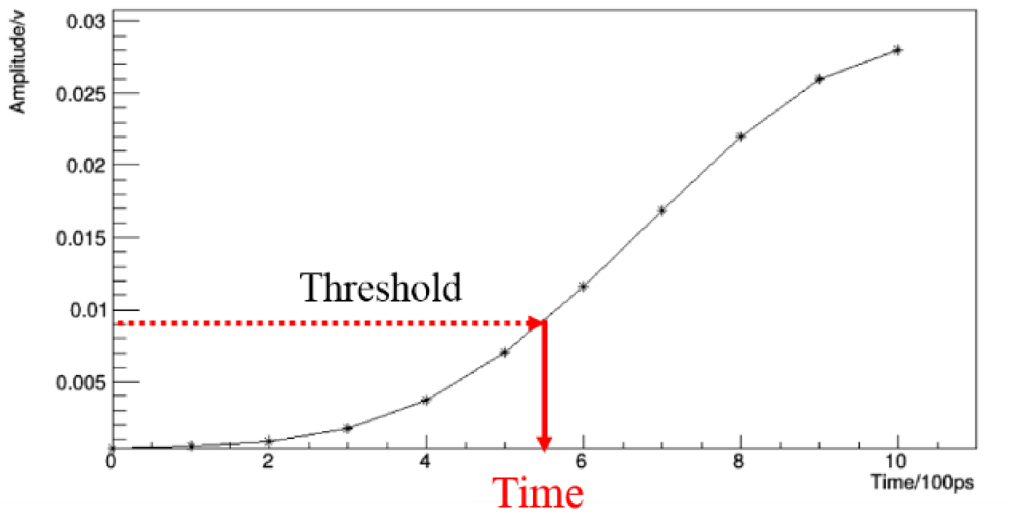
- Proposal of new sMRPC R&D on EIC (ePIC endcaps and/or second IP):
  - ✓ Reduce thickness (less space, less material budget)
  - ✓ Replacement of Eco-friendly gas
  - ✓ Improve spatial resolution
  - ✓ Readout electronics integrated in JLab CODA DAQ system

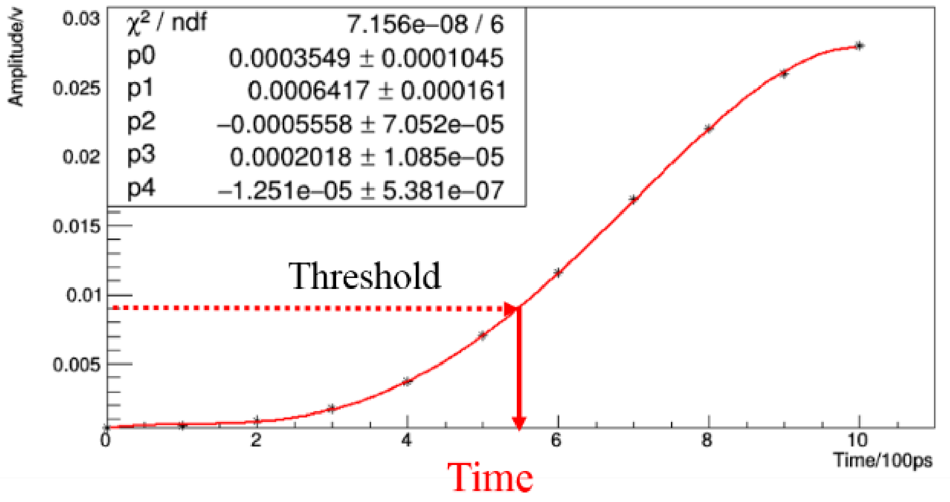
➢ A formally supported EIC R&D program for sMRPC will encourage more funding supports from China

BACKUP

Time Correction

➢ToT Method vs. Sampling





- ❑ ToT Method:
  - ✓ Fixed threshold by DIS
  - ✓ Use ADC for walk-correction
  - ✓ Fewer requirements on front-ends
  - ✓ Affected by signal amplitude
- ❑ Sampling Method:
  - ✓ Capture waveform of raise-edge
  - ✓ Need fast sampling front-ends
  - ✓ Good for high-precision timing
  - ✓ Good for large noise and varying amplitudes

Tsinghua's Sealed MRPC (sMRPC)

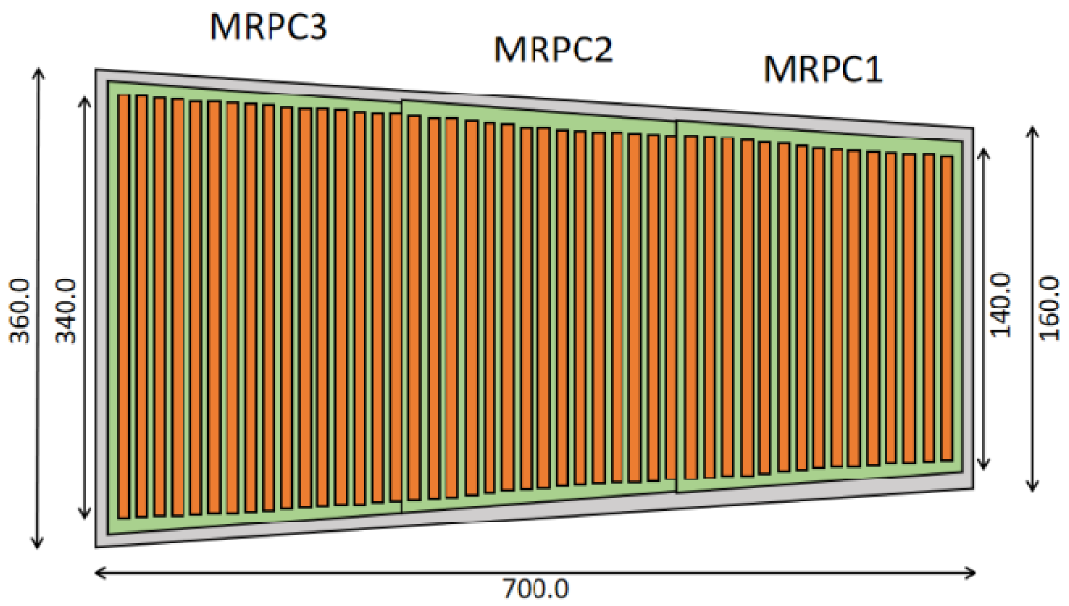
- Parameters of Gen3 sMRPC (32-layers, 400um glass, 128um gap)

MRPC Module	L x W x T (mm)
Honeycoumb Board(x2)	265 x 90 x 7.5
Outer PCB (x2)	298x120x0.6
Inner PCB (x2)	298x120x1.2
Center PCB (x1)	328x120x1.2
Readout Strip (on PCB)	268x5(8 line, 2mm gap)
Mylar film (x2*4)	268x90x0.25
Carbon Electrode (x2*4)	250x72x0.005
Resistive Glass (x9*4)	258x80x0.4
Gas Layer (x8*4)	0.128
Active Area	258 x 80
Total Size	328 x 120 x 40.3 （0.1 X_0)

Pulse signal before PreAMP: 2mV
(integrated charge ~ 4pC)

Hadron Endcap mRPC-TOF

Endcap TOF consists of 16 modules and each module consists of 3 sealed MRPC.



Total overlapped thickness= 60mm

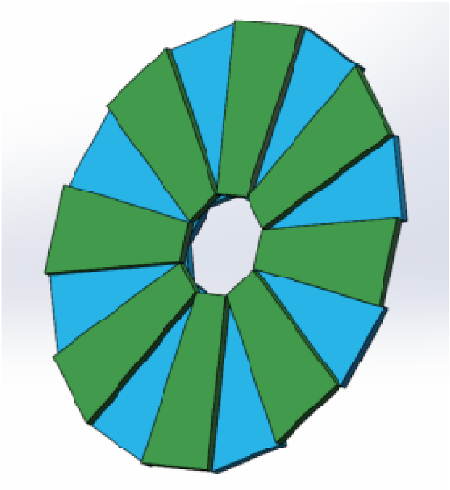
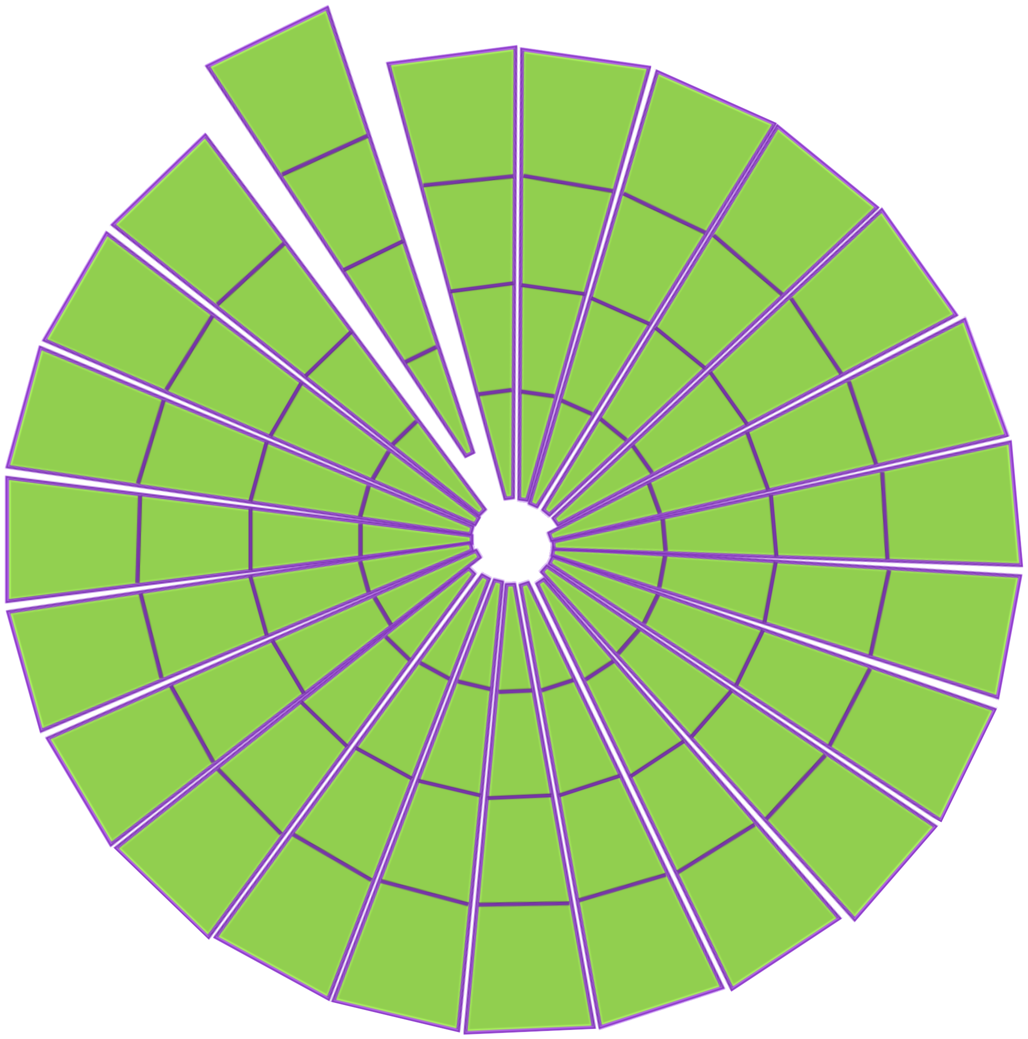


Figure 1.3 Arrangement of MRPCs inside the box in the End-cap.

Hadron Endcap mRPC-TOF



mRPC Modules:

- $30K per m^2 for 32 gas-layers with regular low-resistive glasses
- For a 180cm outer radius and 10cm inner radius disk, it takes 10m^2 of mRPC
- Total cost: $0.3M

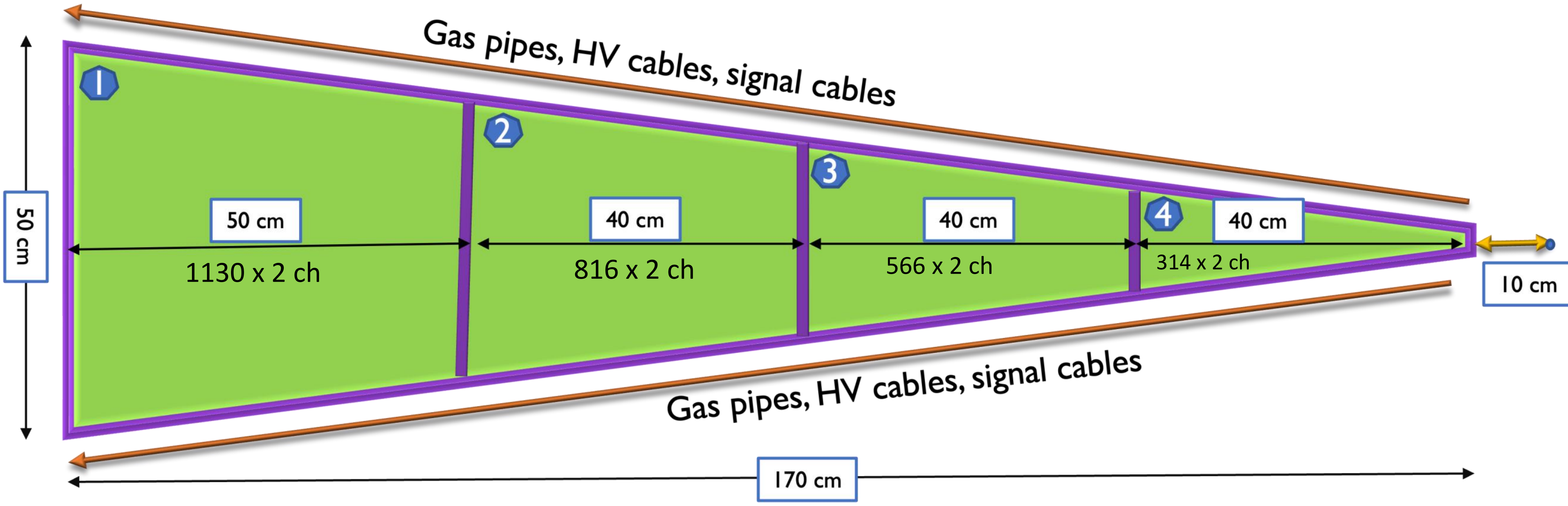
Readout Electronics:

- 1cm for each channel, read from both ends along the radial direction
  - Module#1: 51 x 2 channels
  - Module#2: 37 x 2 channels
  - Module#3: 25 x 2 channels
  - Mudule#4: 14 x 2 channels
- Total channels of each sector: 254 channels
- Total 22 sectors → 5588 channels ~ 5600 channels
- Total cost: $500 for each channel → $2.8M for readout electronics

HV Supplies:

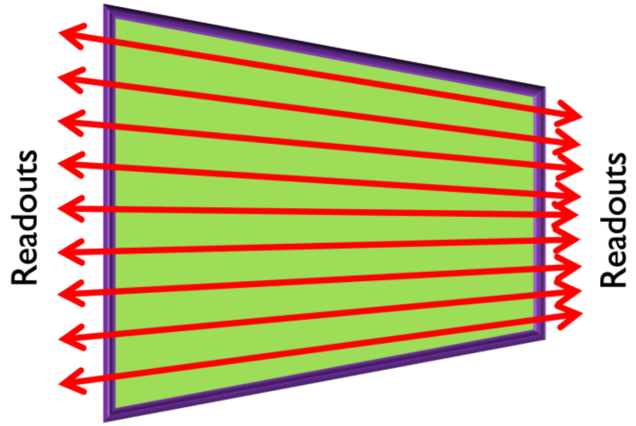
- CAEN AG524P → 6 HV outputs, quote $6K for each board
- Two module power one sector (positive + negative polarity)
- Total 44 HV boards
- Nee two frames that house the HV boards → $8K for each
- Total: $280K for HV power supplies
- Cables: $??K

Hadron Endcap mRPC-TOF

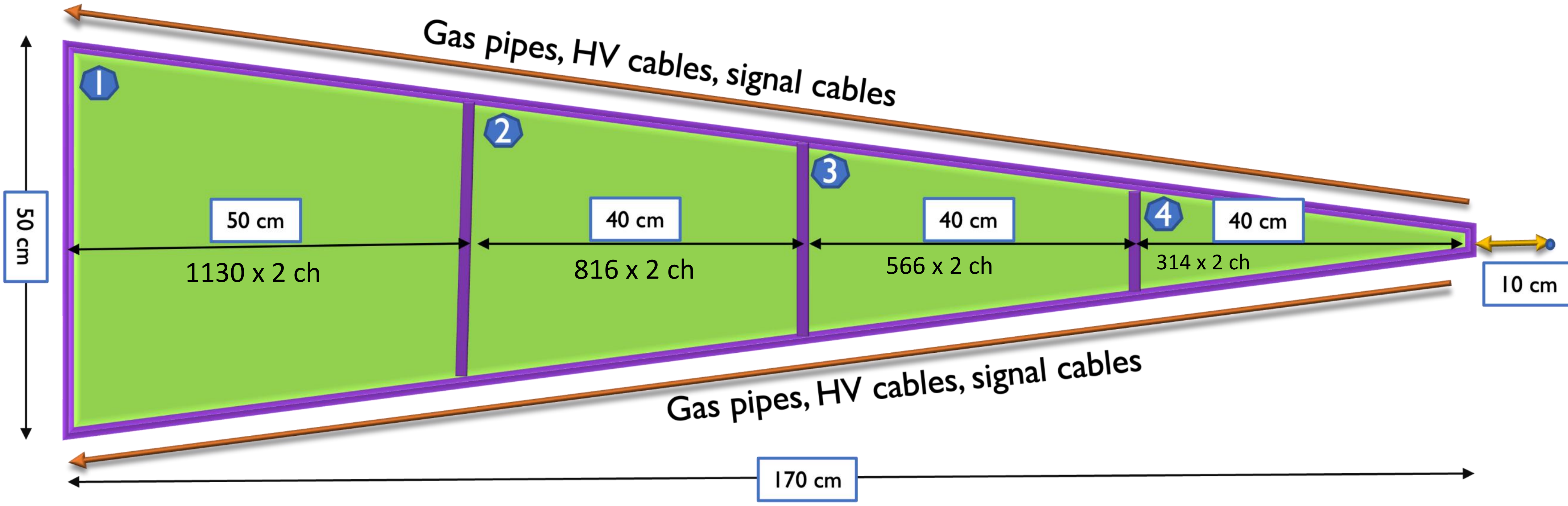


<u>Each mRPC Super-Module:</u>

- Divide the total disk into 22 sectors
- Each sector contains a super-module with 4 individual mRPC modules with different sizes
- For each mRPC module, read the signal from both ends along the radius direction

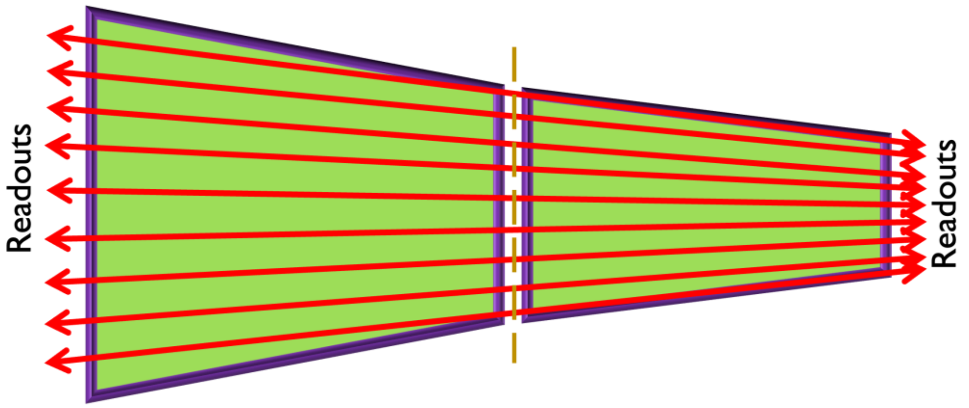


Hadron Endcap mRPC-TOF



Each mRPC Super-Module:

- Divide the total disk into 22 sectors
- Each sector contains a super-module with 4 individual mRPC modules with different sizes
- For each mRPC module, read the signal from both ends along the radius direction
- Alternatively: Chain the strips of two (or all four) neighboring mPRCs to save more readouts → How much timing resolution we will lost?



Refrigerant Name	CAS Name	AR2	AR3	AR4	AR5	Manufacturer
R-10	Carbon tetrachloride		1,800.00	**1,400.00**	1,730.00	
R-11	Trichlorofluoromethane		4,600.00	**4,750.00**	4,660.00	
R-113	1,1,2-Trichlorotrifluoroethane		6,000.00	**6,130.00**	5,820.00	
R-1132a	Vinylidene fluoride				**<1**	
R-114	CFC 114		9,800.00	**10,000.00**	8,590.00	
R-115	1-Chloro-1,1,2,2,2-pentafluoro		7,200.00	**7,370.00**	7,670.00	