MRPC technology for TOF system

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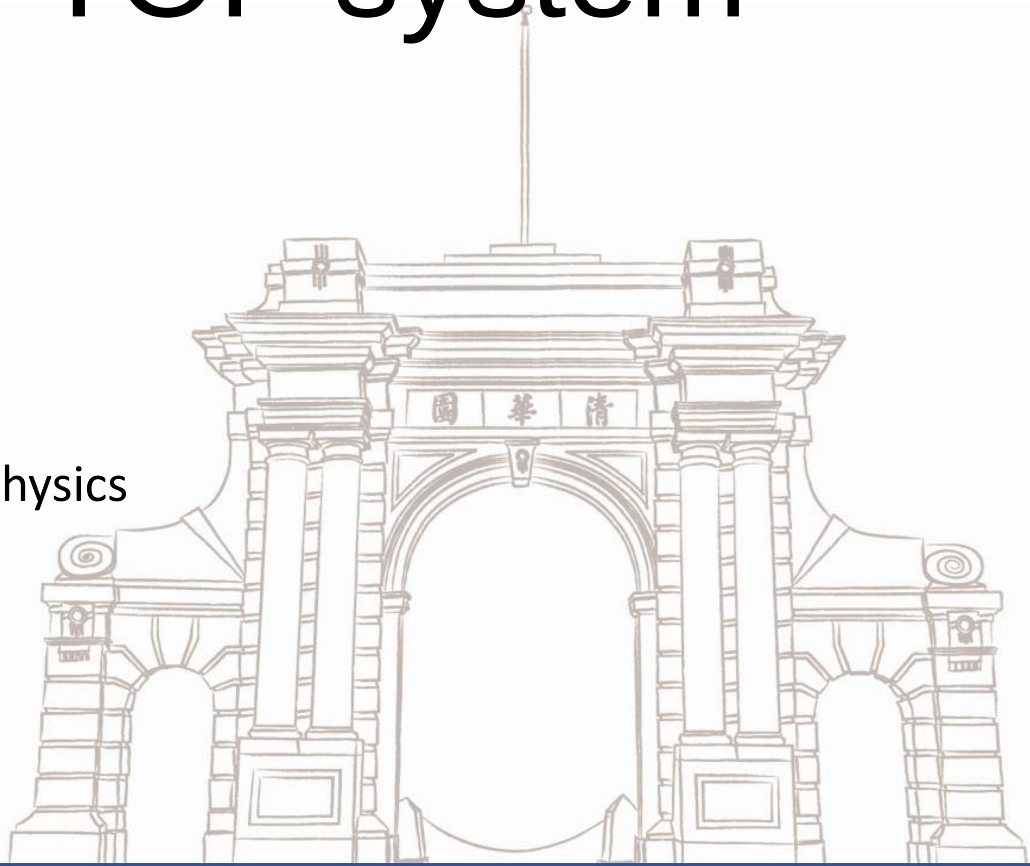


Outline

- Introduction of MRPC -TOF system and important physics results
- Future requirement for MRPC-TOF:

  -- High rate >20kHz/cm^2

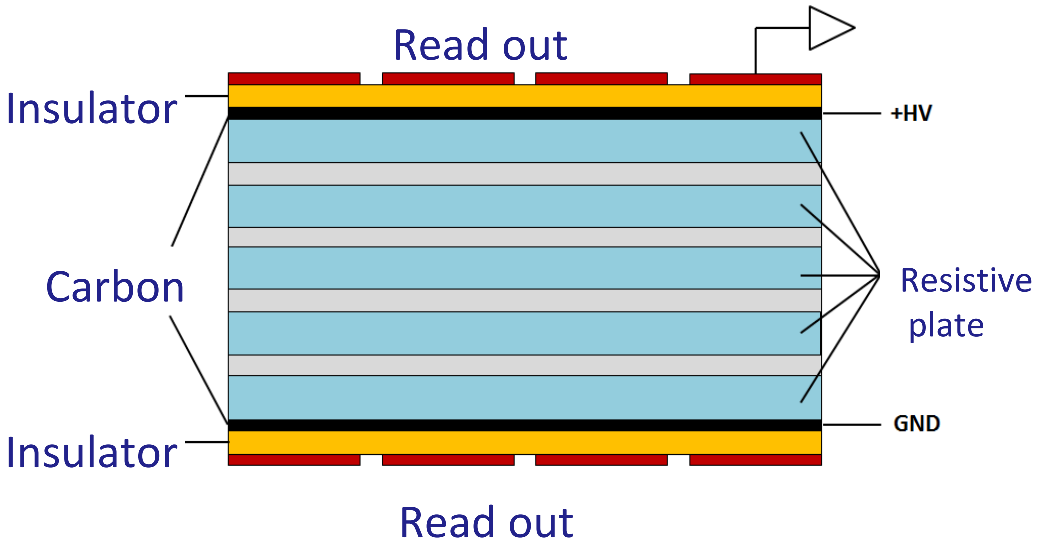
  -- High time resolution <20ps

  -- Use sealed MRPC to reduce gas consumption

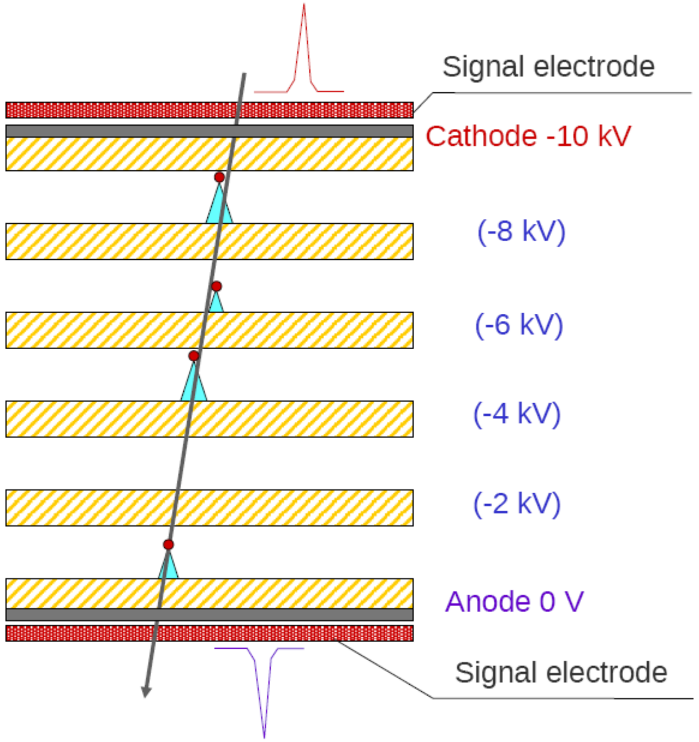
  -- Find Eco-friendly working gas

- Summary

MRPC introduction



MRPC structure



stack of equally-spaced resistive plates with voltage applied to external surfaces (all internal plates electrically floating)

pickup electrodes on external surfaces (resistive plates transparent to fast signal)

internal plates take correct potential – initially due to electrostatics but kept at correct potential by flow of electrons and positive ions - feedback principle that ensures equal gain in all gas gaps

主要优点:

时间分辨达到： 几十ps量级

探测效率：>98%

造价便宜

长期工作稳定！

MRPC application：

1. Application in nuclear physics experiments
2. Application in industry（Muon tomography)
3. Application in medicine（TOF-PET）

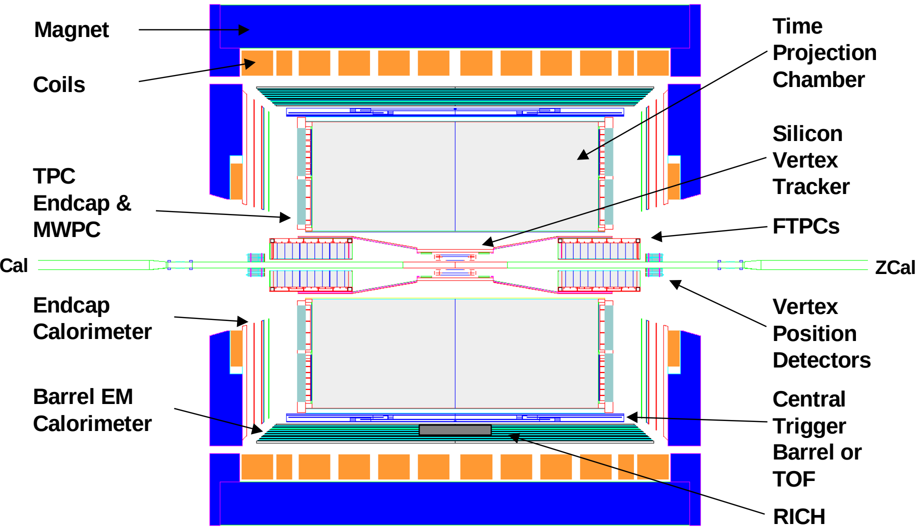
MRPC in ToF system

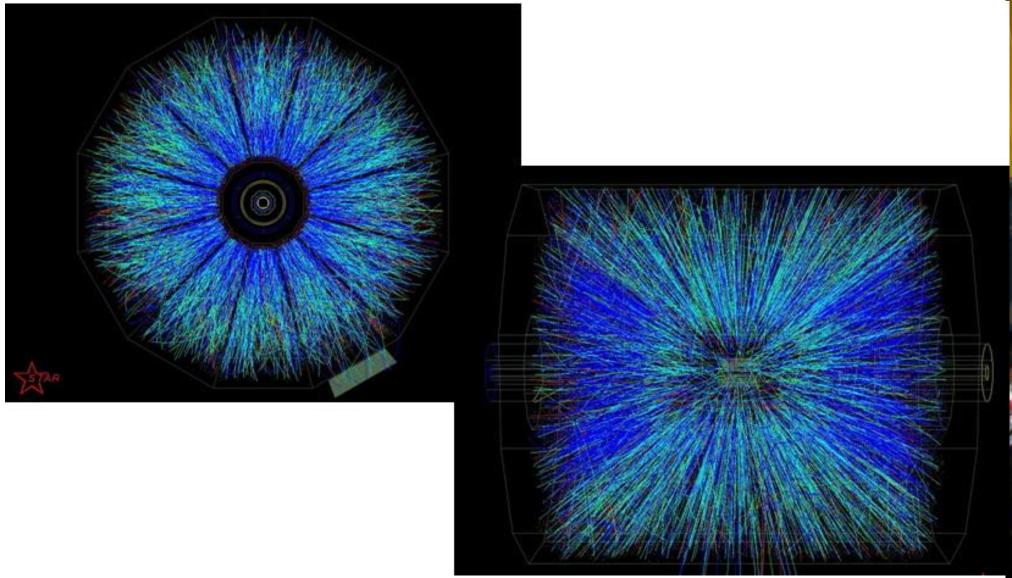
MRPC has been widely adopted to construct the Time of Flight (TOF) systems in HEP experiments.

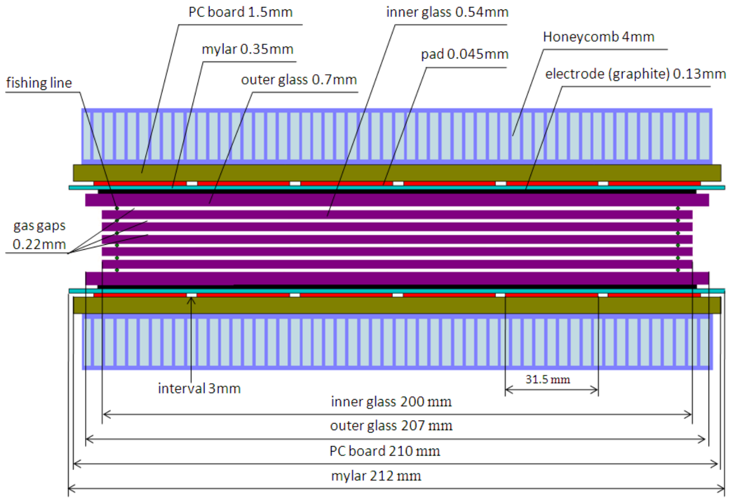
	ALICE	STAR	FOPI	BESIII	CBM	SoLID
Active area per detector (cm)	120 x 13	22 x 8.4	90 x 4.6	0.5x(9.2+14.8)x 32.8	33 x 27.6	--
Total active area (m^2)	141	50	5	1.33	120	10
Pad size (cm)	3.7 x 2.5	6.3 x 3.1	90 x 0.3	(9.1~14.1) x 2.4	27 x 1.0	(16~28) x 2.5
Gap×thickness(mm)	10 x 0.25	6 x 0.22	6 x 0.3	12 x 0.22	10 x 0.25	32 x 0.128
Gas mixtures ($C_2H_2F_4$/ C_4H_{10}/SF_6)	90/5/5	95/5/0	85/5/10	90/5/5	90/5/5	90/5/5
Operating field (kV/cm)	96	107	110	109	110	140
Efficiency	99.9%	95-97%	97±3%	99%	97%	98%
Time resolution(ps)	40	60	73±5	60	60	**20 ps**
Max rate (Hz/cm^2)	50	10	50	50	**30k**	**20k**

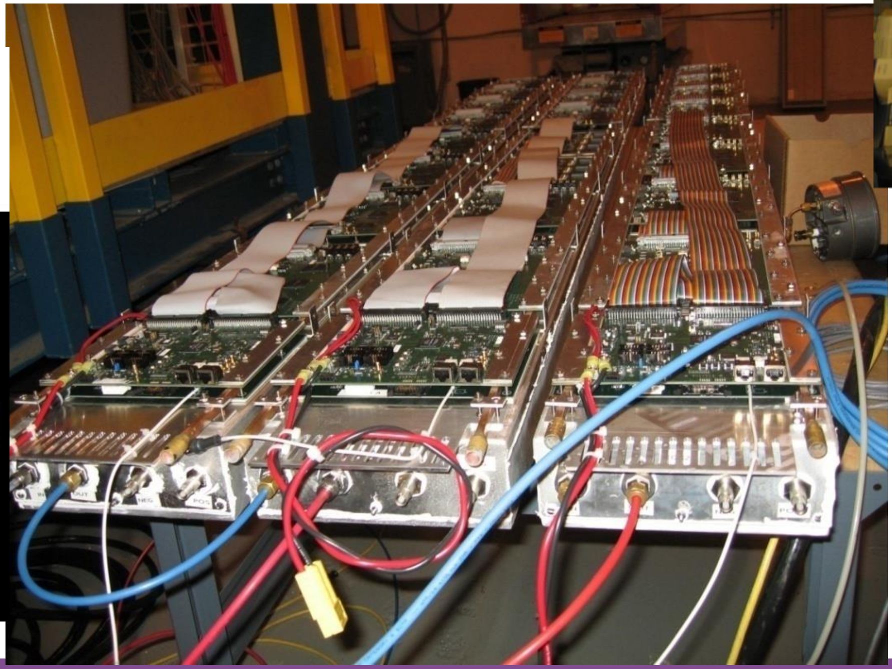
higher **counting rate** and **time precision**.

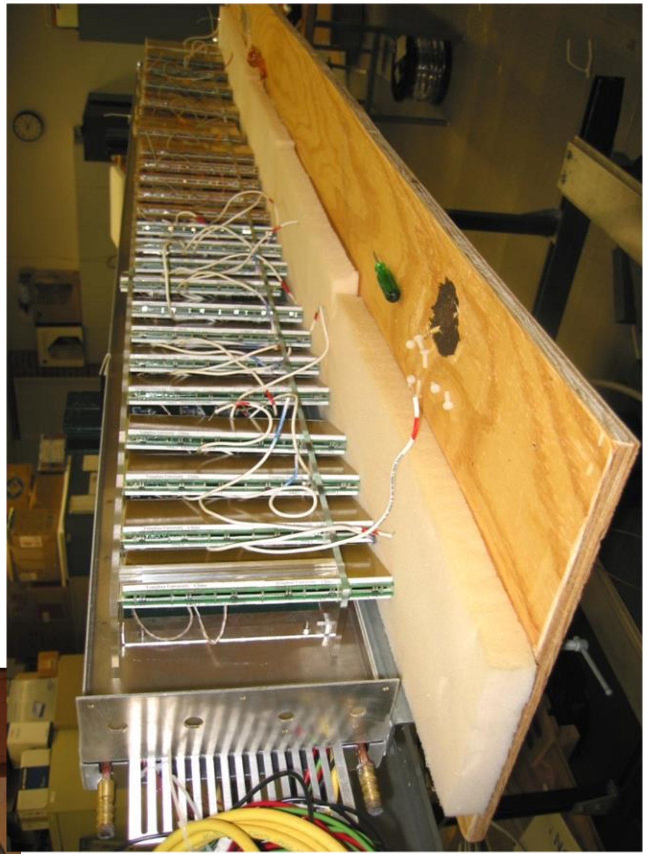
RHIC-STAR TOF system





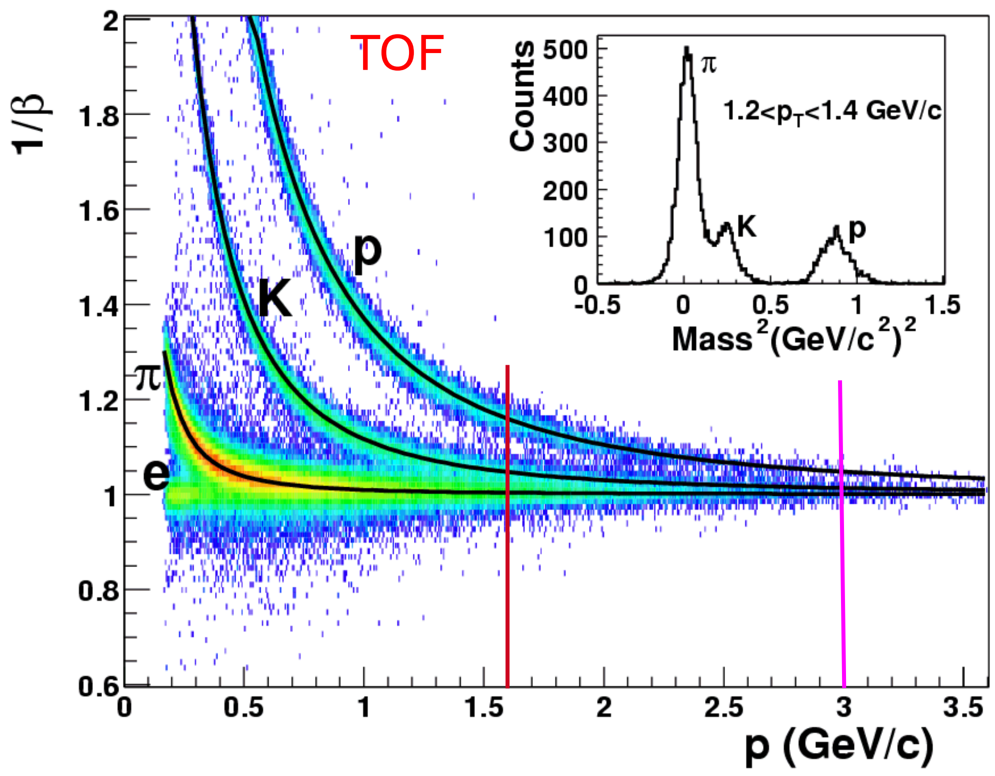






STAR TOF-Tray

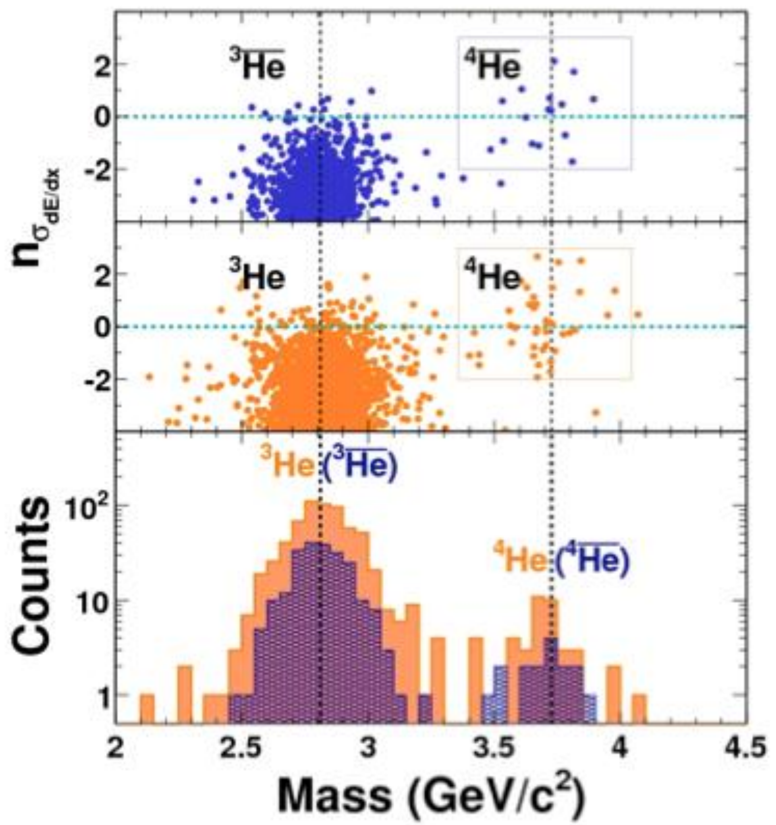
PID and physics success



TOF PID:

π /k ~1.6 GeV/c,

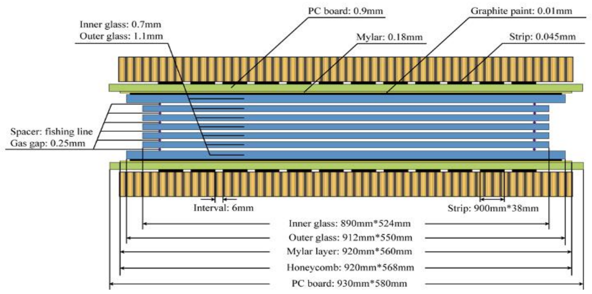
(π,k)/p ~ 3.0 GeV/c



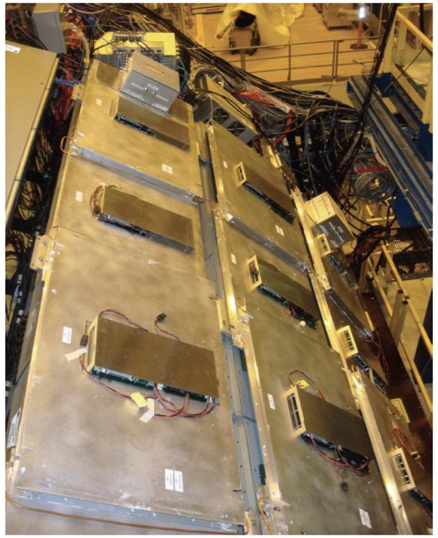
Observation of the antimatter helium-4 nucleus

The STAR Collaboration* ***Nature 473 (2011) 353***

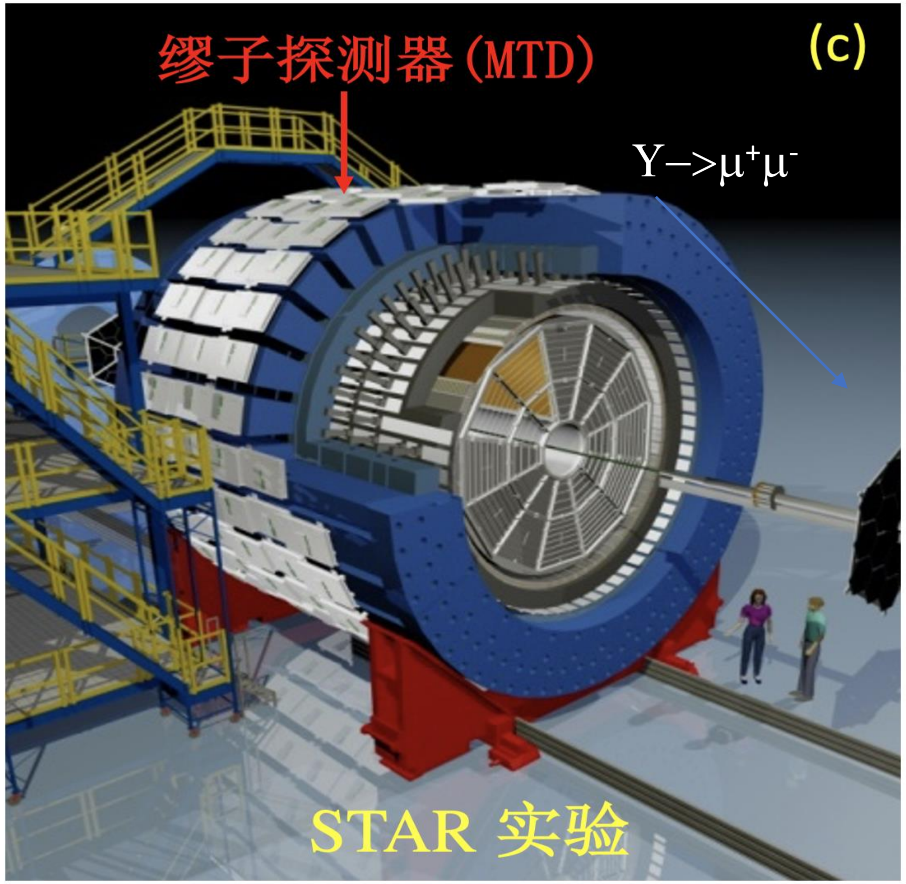
PID and physics success

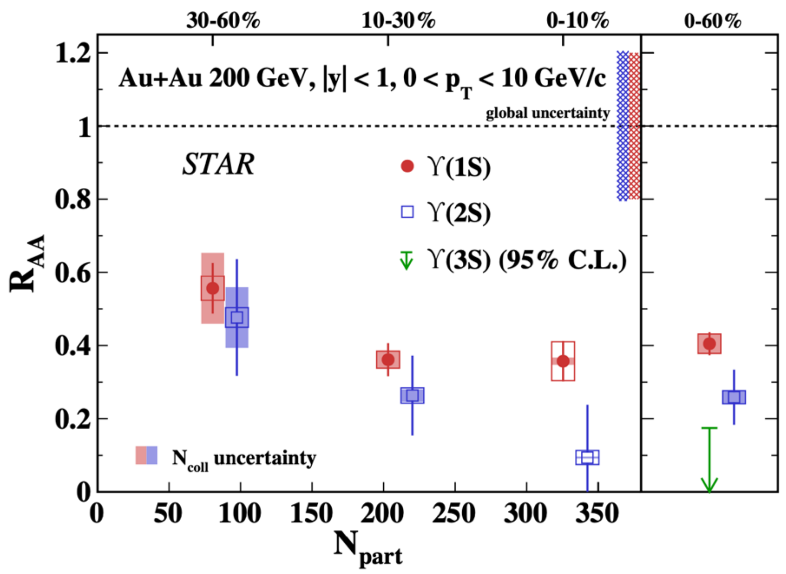


(a)



(b)





STAR实验在200 GeV金核-金核碰撞中发现底夸克偶素“顺次压低”的实验迹象.

The STAR Collaboration* Phys. Rev. Lett. 130 (2023) 112301

2014年，STAR采用MRPC技术建造了新型的缪子探测器，通过测量双缪子的信号来重建底夸克偶素。MRPC的优秀时间分辨率（70ps）可以压低强子本底，提高双缪子道的时间窗匹配精度。

Future requirement for MRPC-TOF

- High counting rate: >20kHz/cm^2

  Electrode material, detector structure, spacer…

- High time resolution: <20ps

  Detector structure, readout electronics (FEE + sampling, TDC…)

- Economic and lower gas consumption

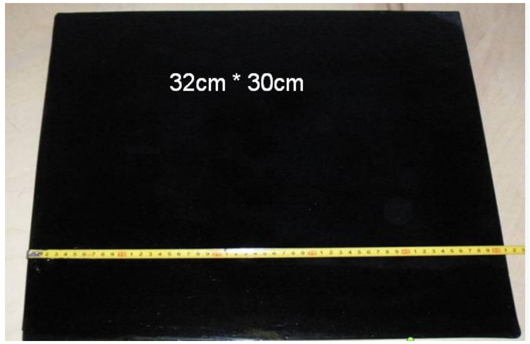
  Detector structure, eco-gas…

Higher counting rate: low-resistive glass

- low-resistive glass control the voltage drop (efficiency loss) when incident flux goes up by Decrease the resistivity of the electrodes

$$V_{gap} = V_{ap} - \bar{V}_{drop}$$

$$\bar{V}_{drop} = \bar{I}R = \bar{q}\Phi\rho d$$

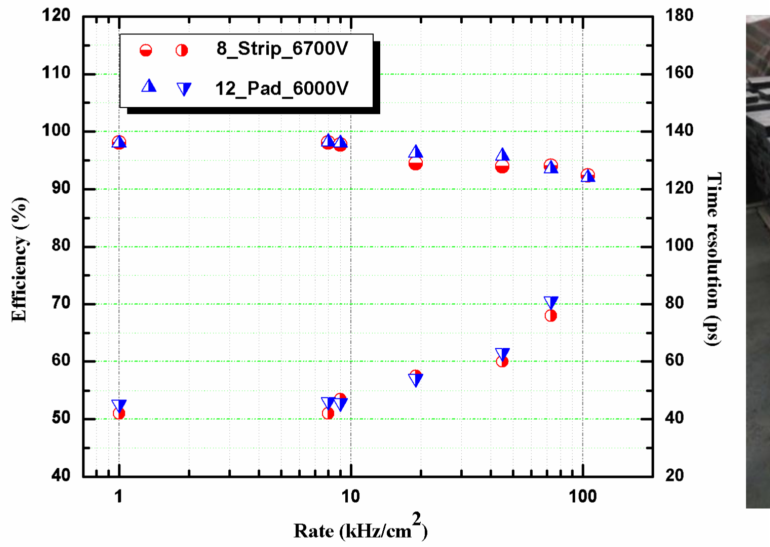


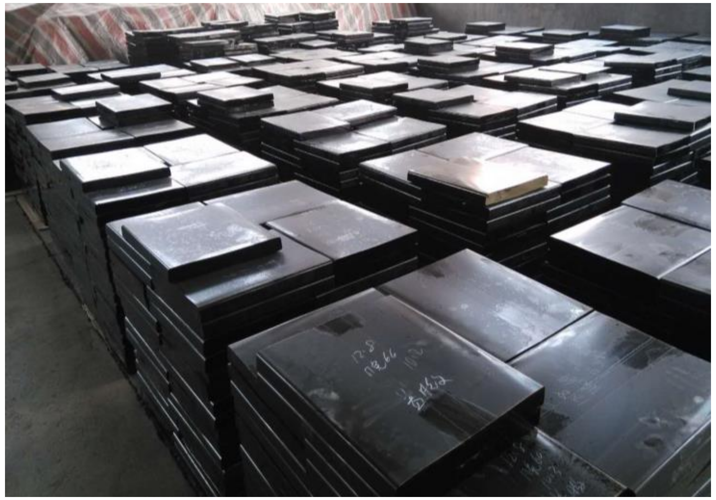
Specifications of low resistive glass

Maximal dimension	32cm × 30cm
Bulk resistivity	10^{10} Ωcm
Standard thickness	0.7, 1.1mm
Thickness uniformity	20 μm
Surface roughness	< 10nm
Dielectric constant	7.5 - 9.5
DC measurement	Ohmic bebavior stable up to 1 C/cm^2

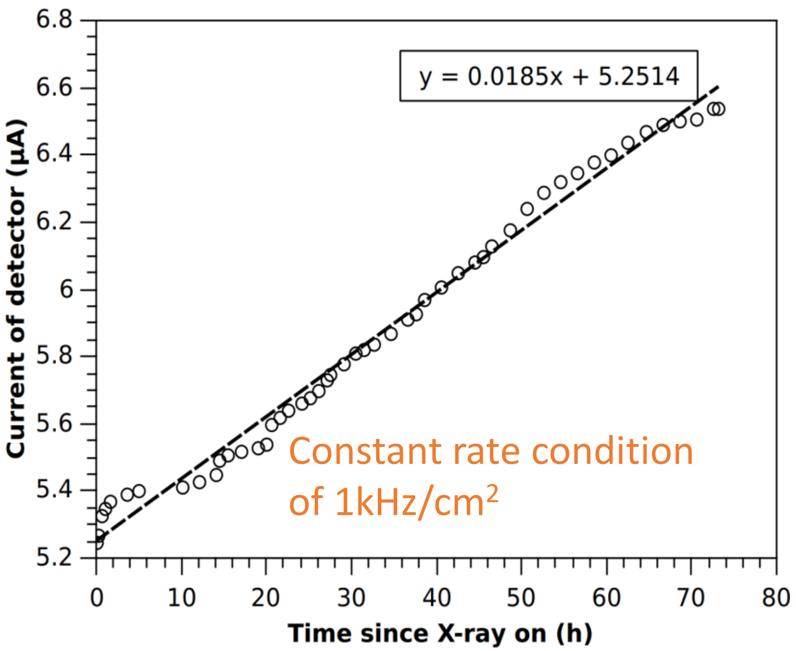
- Low-resistive glass has been operating at FAIR-Phase 0 programs like STAR-eTOF and mCBM
- It has been applied in CBM-ToF Wall
- Beam test result:

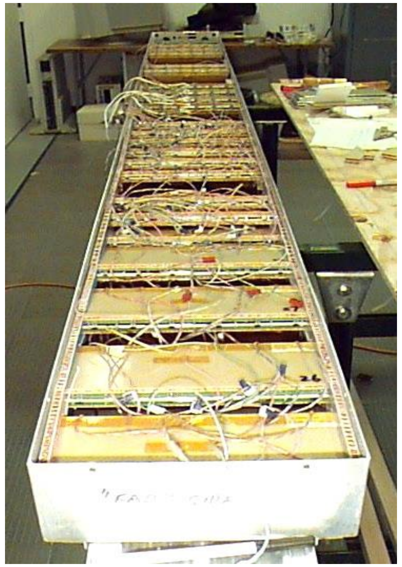
  93%, 80ps ,70kHz/cm²

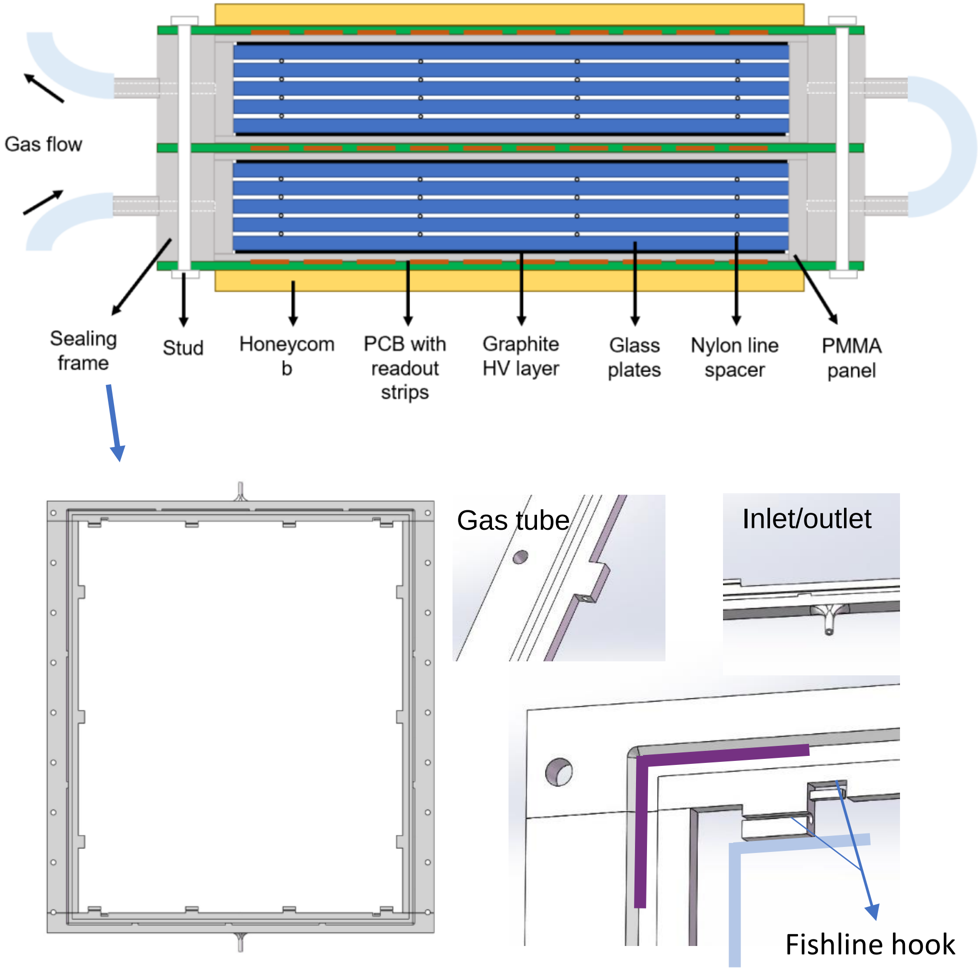




Higher counting rate (<7kHz/cm^2): gas pollution







3D printed sealing frame with Good strength, insulation and radiation persistency

- The gas pollution in the gas gap caused the increase of current!

- Sealing MRPC speed up gas exchange and can reduce to 1sccm/m^2 flush rate at cosmic experiment!

Excellent performance of sealed MRPC

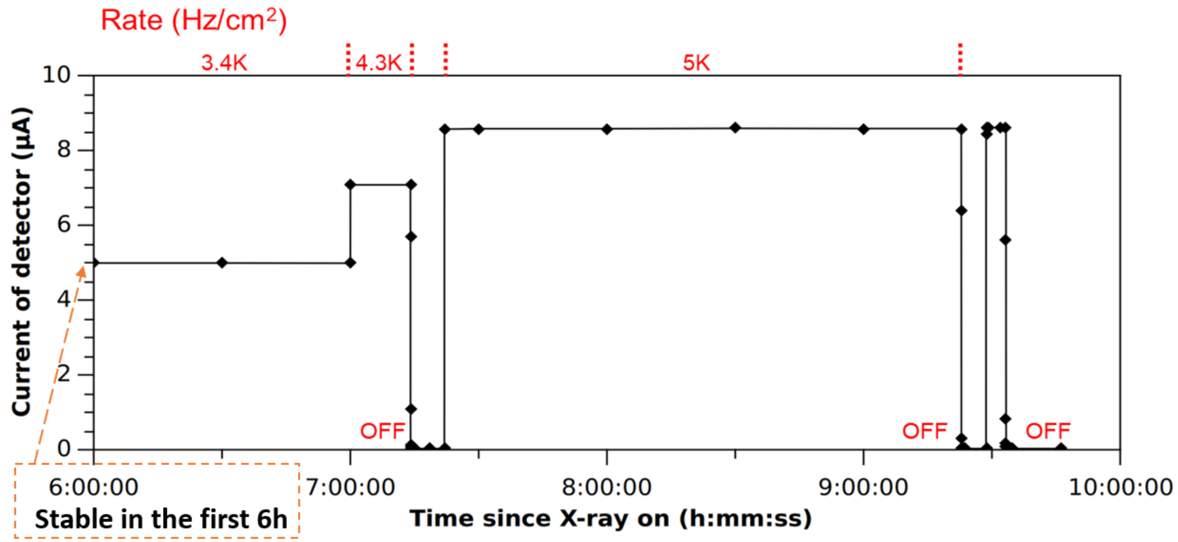
Sealed MRPC promoted gas exchange

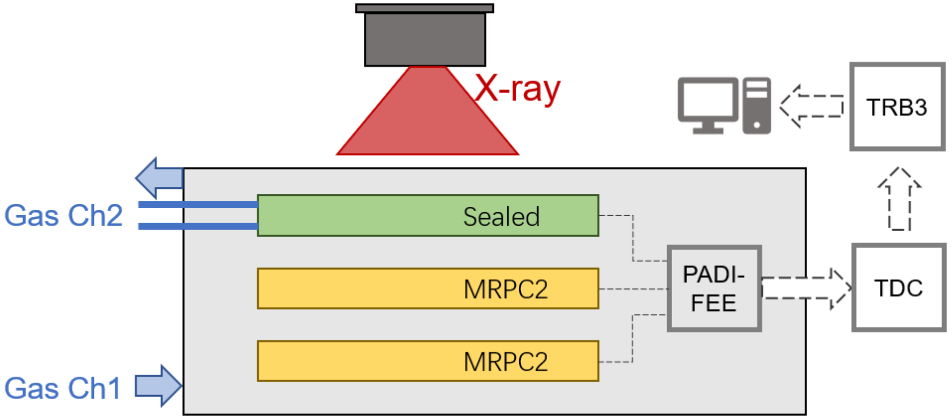
Decrease the wait time of gas purging:

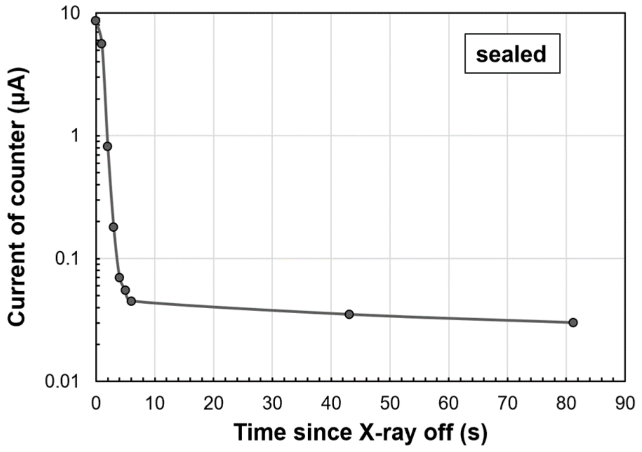
- Reach the working HV in 2h since flowing the gas

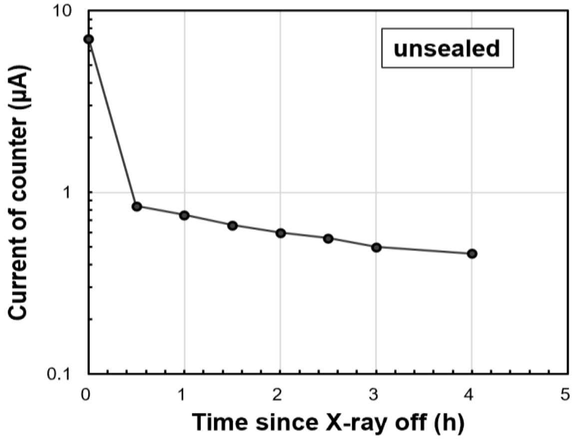
Excellent current behavior under high rate irradiation:

- Stable current with constant rate condition.
- Fast decay of dark current since when X-ray is off

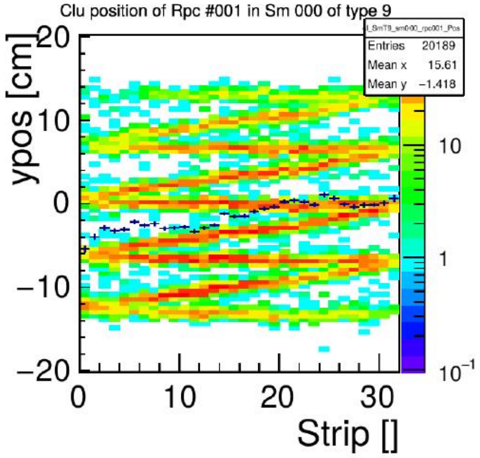


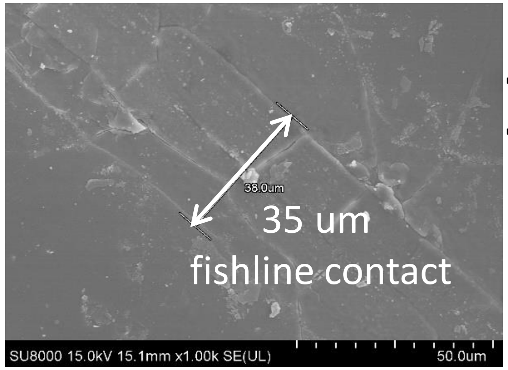


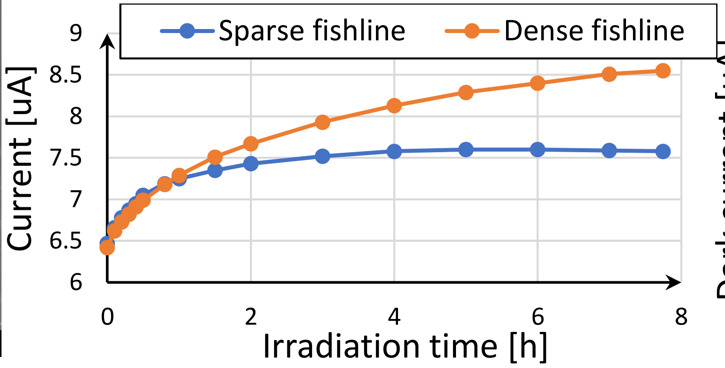


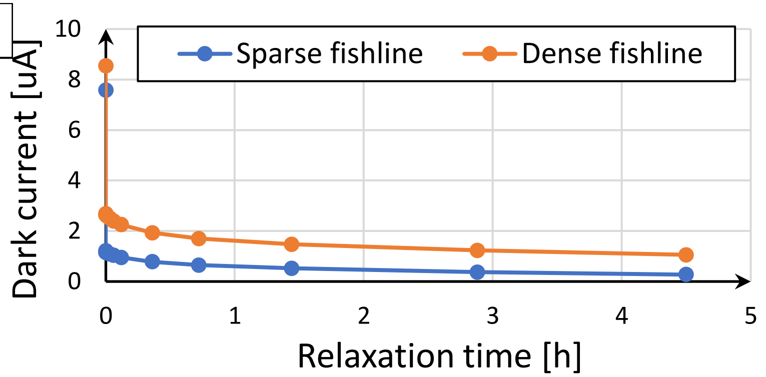


High counting rate (>7kHz/cm^2): creepage on fishing line

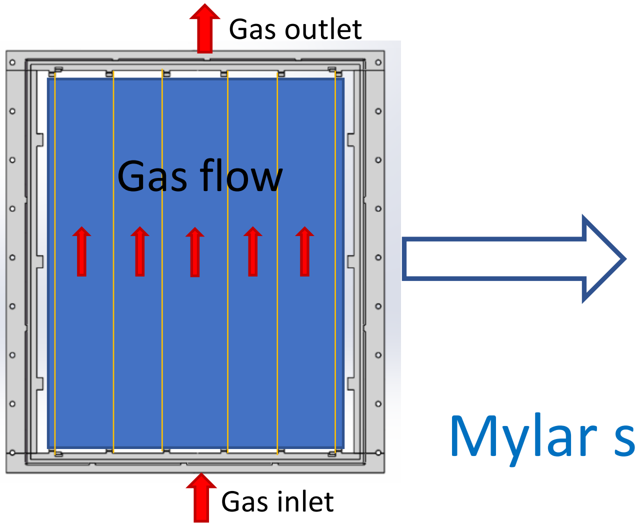




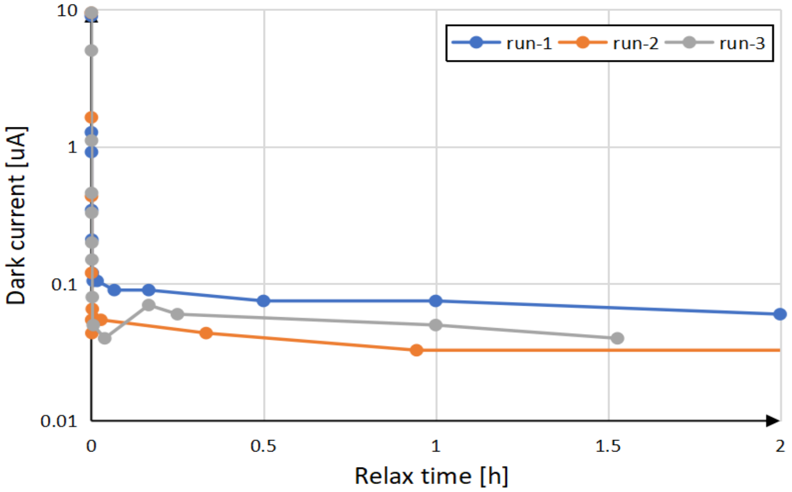




- The creepage on the fishing line caused the high current and deposition!

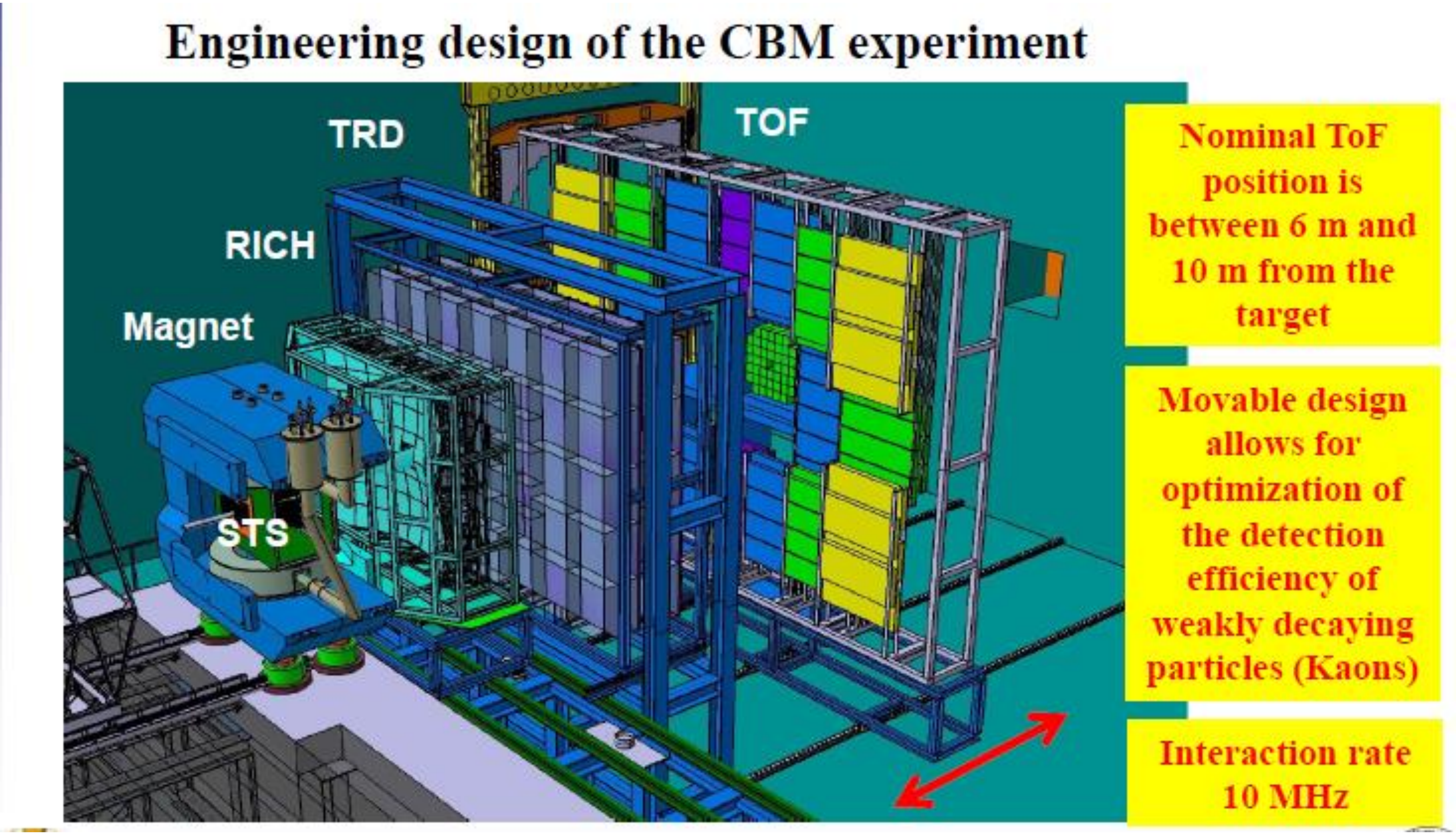


Mylar spacer: 3 x 3 x0.25mm



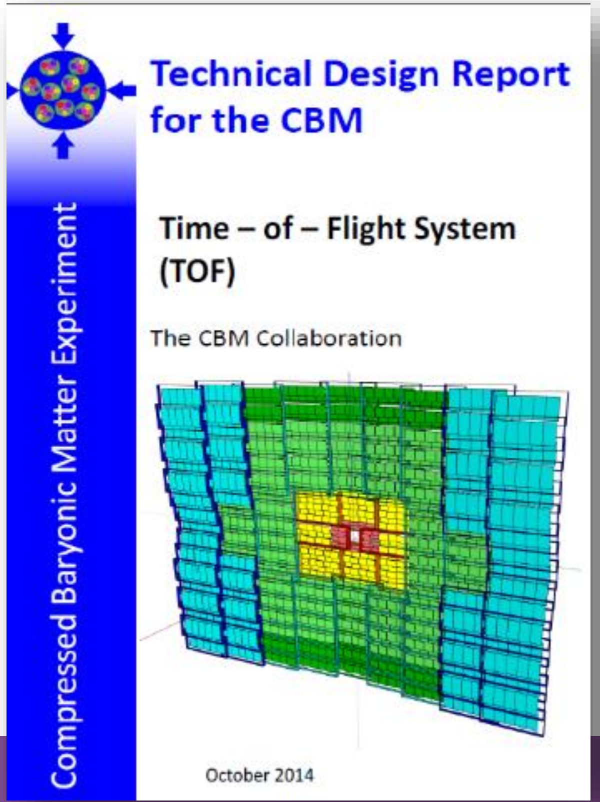
Dark current decay after 10h @7 kHz/cm^2 radiation

The structure of CBM-TOF wall

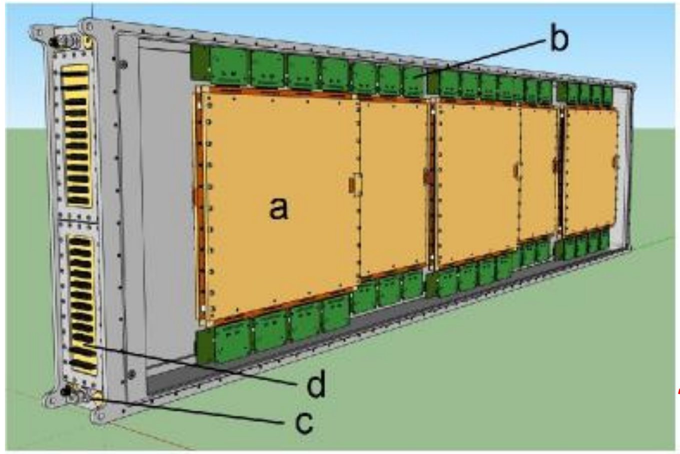


CBM-ToF Requirements

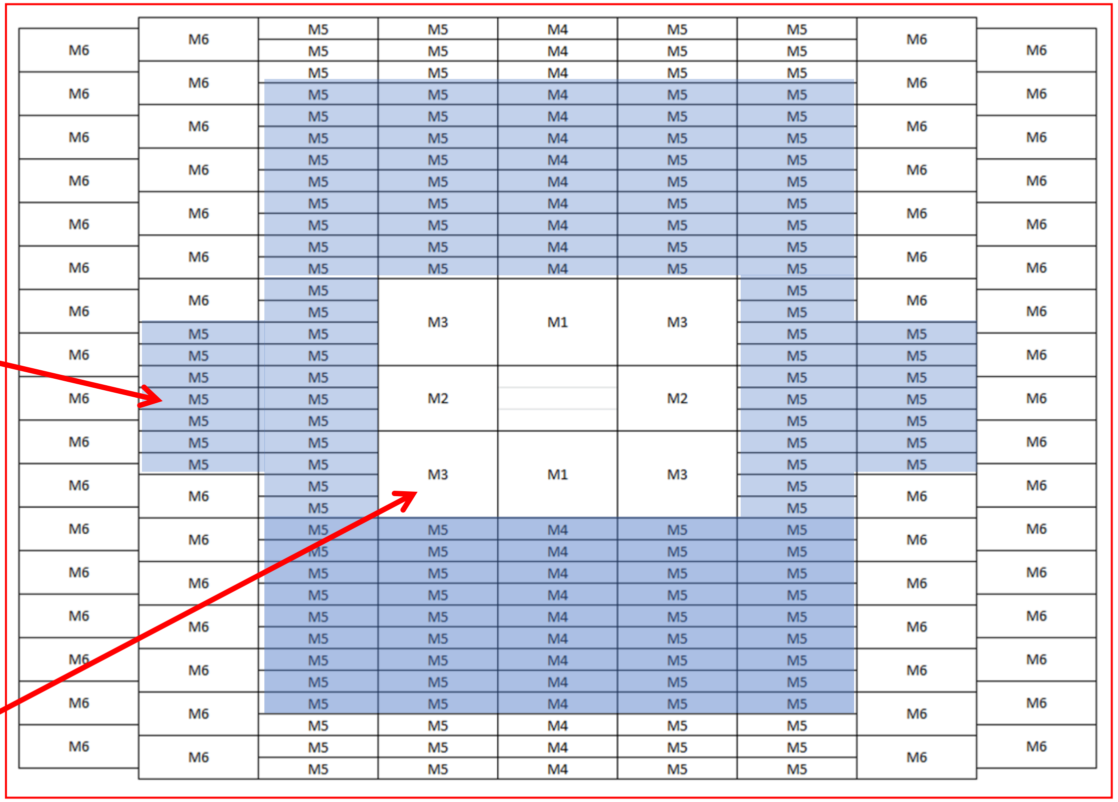
- Full system time resolution σ_T ~ 80 ps
- Efficiency > 95 %
- Rate capability ≤ 25 kHz/cm^2
- Polar angular range 2.5° – 25°
- Occupancy < 5 %
- Low power electronics (~100.000 channels)
- Free streaming data acquisition



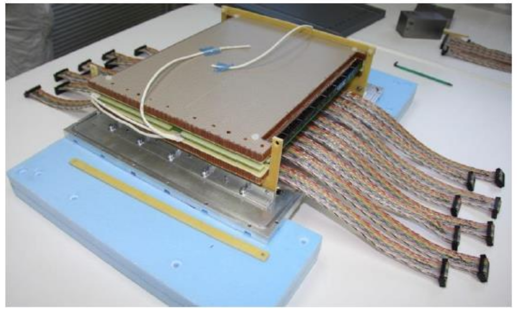
Prototype design for CBM-TOF

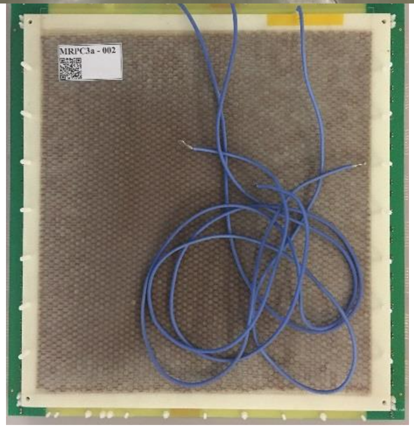


Strip-MRPC



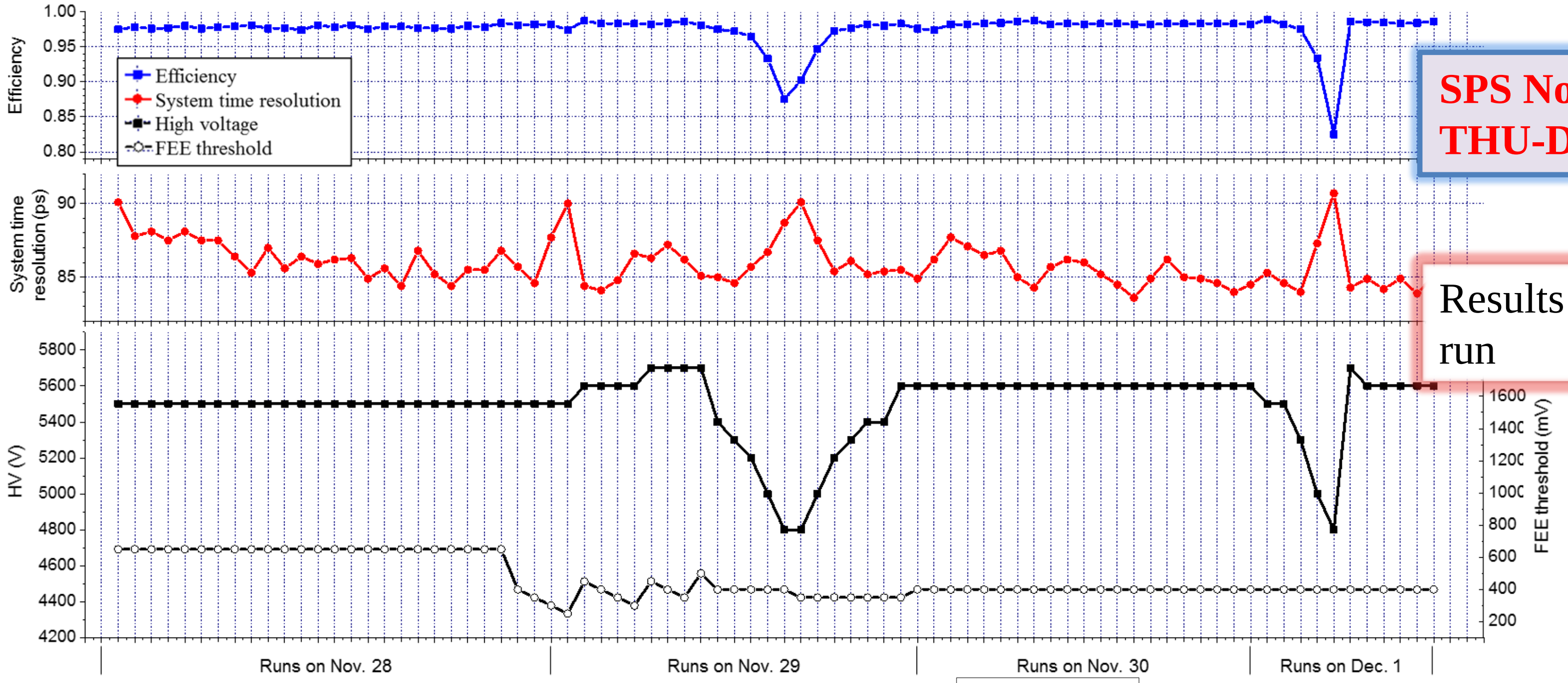
Inner zone-MRPC





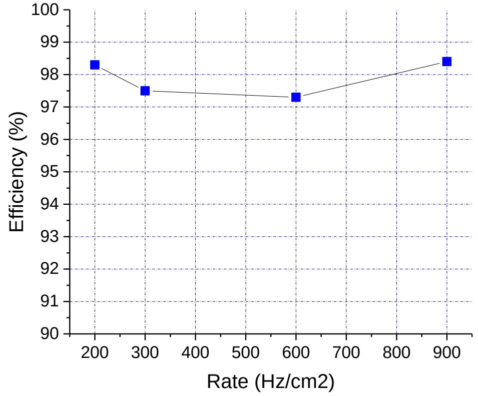
Two-dimensional code of MRPC

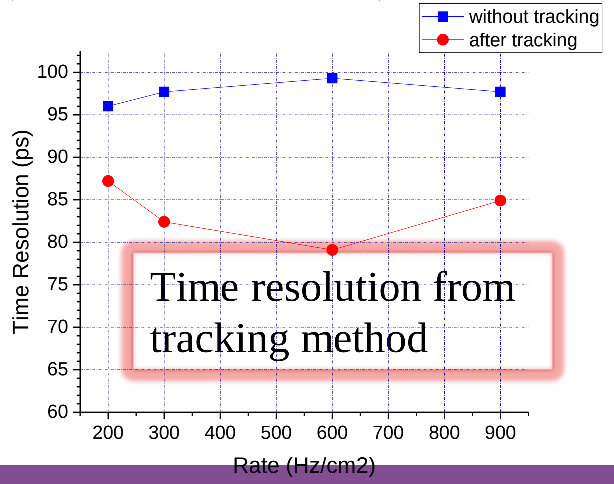
Performance of the prototype



SPS Nov 2015
THU-DU results

Results of each run

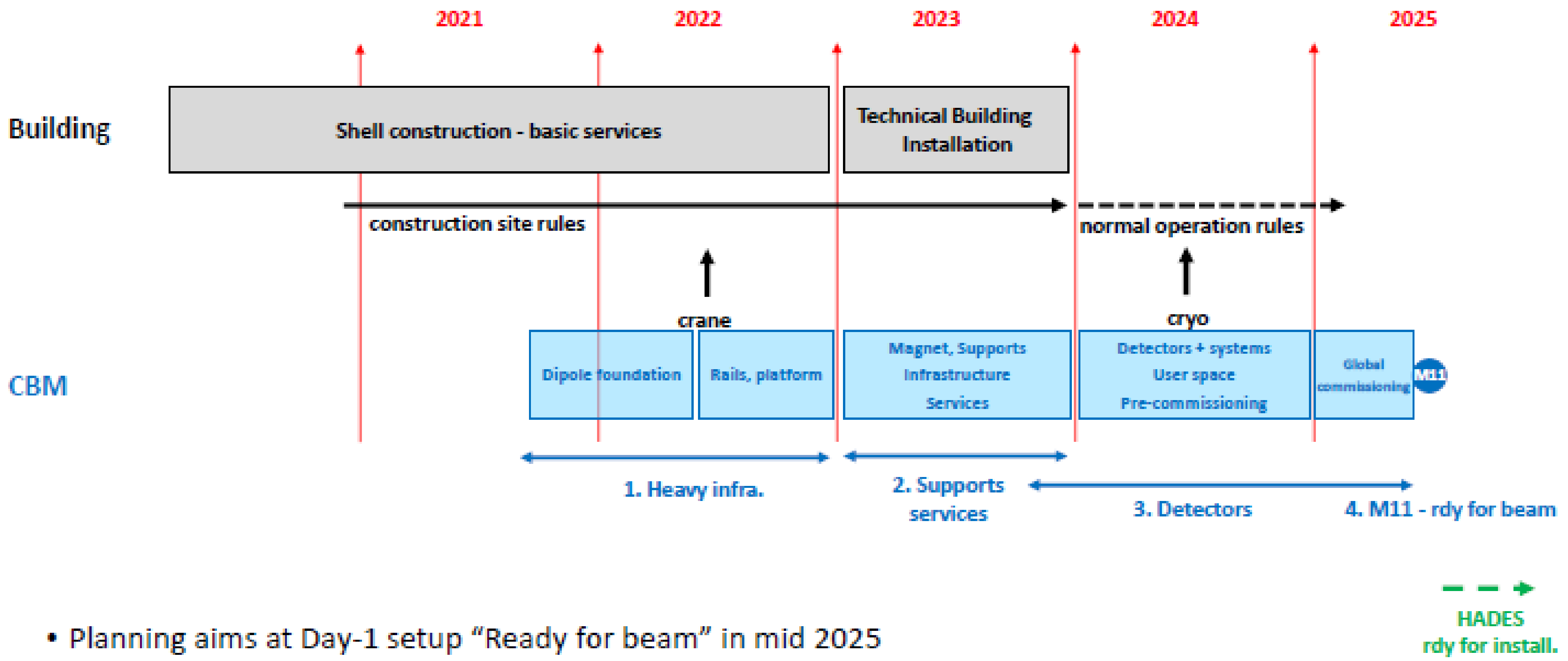




Time resolution from tracking method

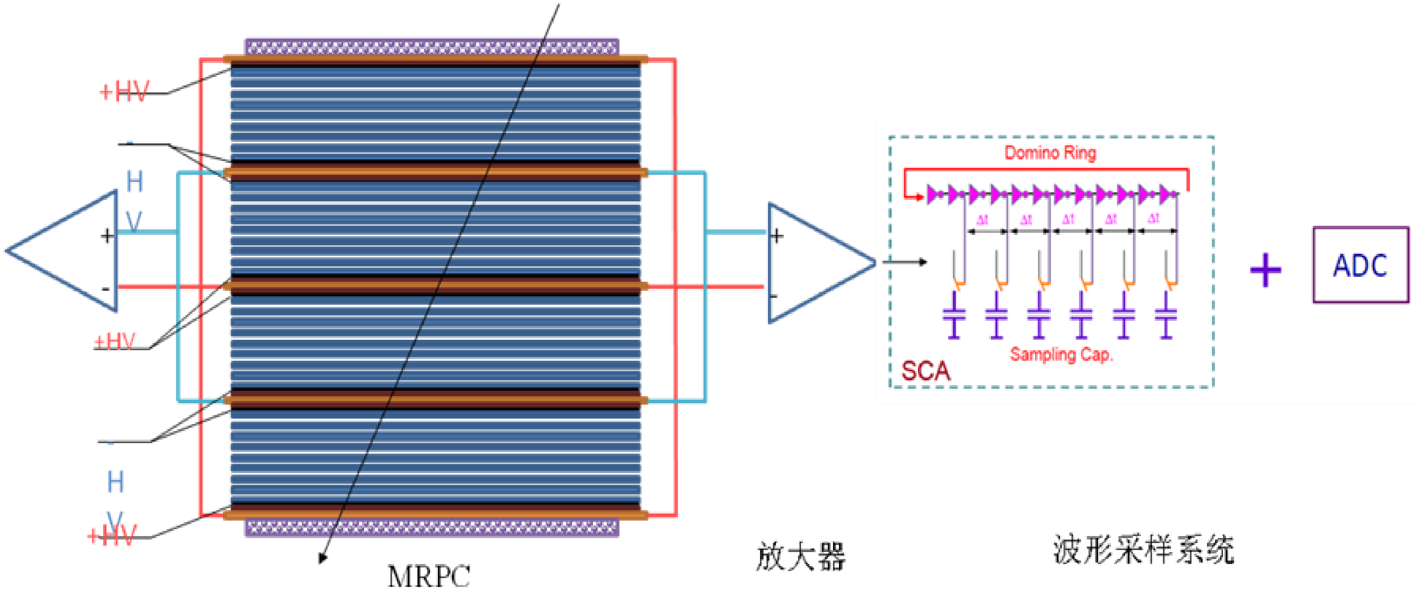
Performance:
Time resolution: <60ps
Efficiency: >98%
Cluster size: <1.6

CBM installation – baseline 2021



- Planning aims at Day-1 setup “Ready for beam” in mid 2025
- Planning based on availability of “secured” funds as declared by funding agencies at the RRB meetings

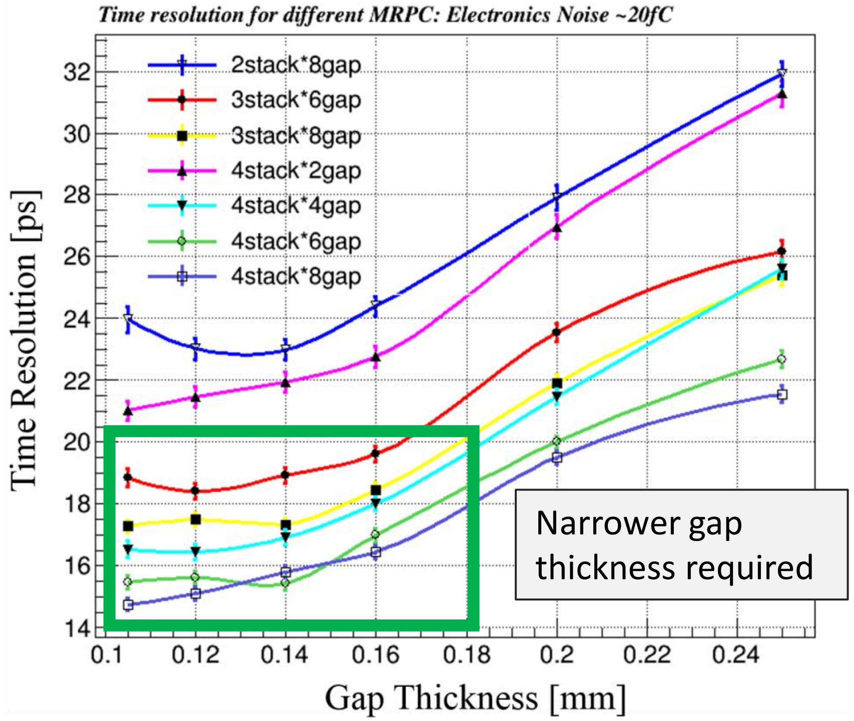
Toward 20ps resolution: narrow gap MRPC



$$\sigma_{TOF} = \sqrt{\sigma_{MRPC} + \sigma_{electronics}}$$

σ_{TOF} <20 ps， the intrinsic resolution of narrow gaps MRPC is around 15ps， so the time jitter of readout electronics <13~15 ps。

- Simulation indicates proper ways to design the gap thickness and arrange the stacks

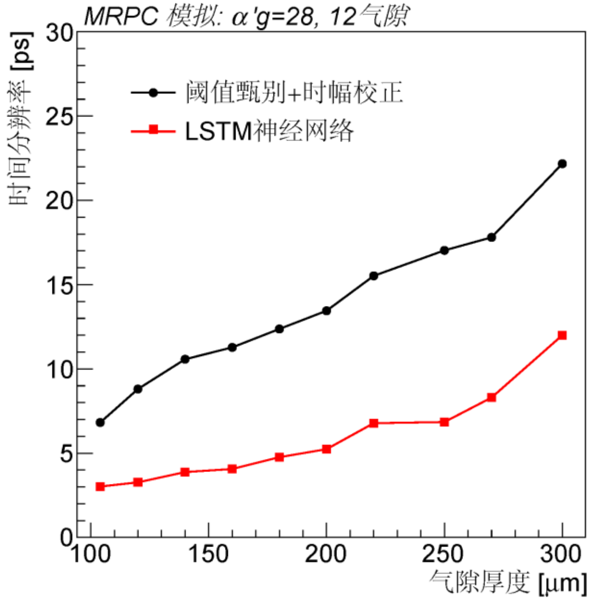


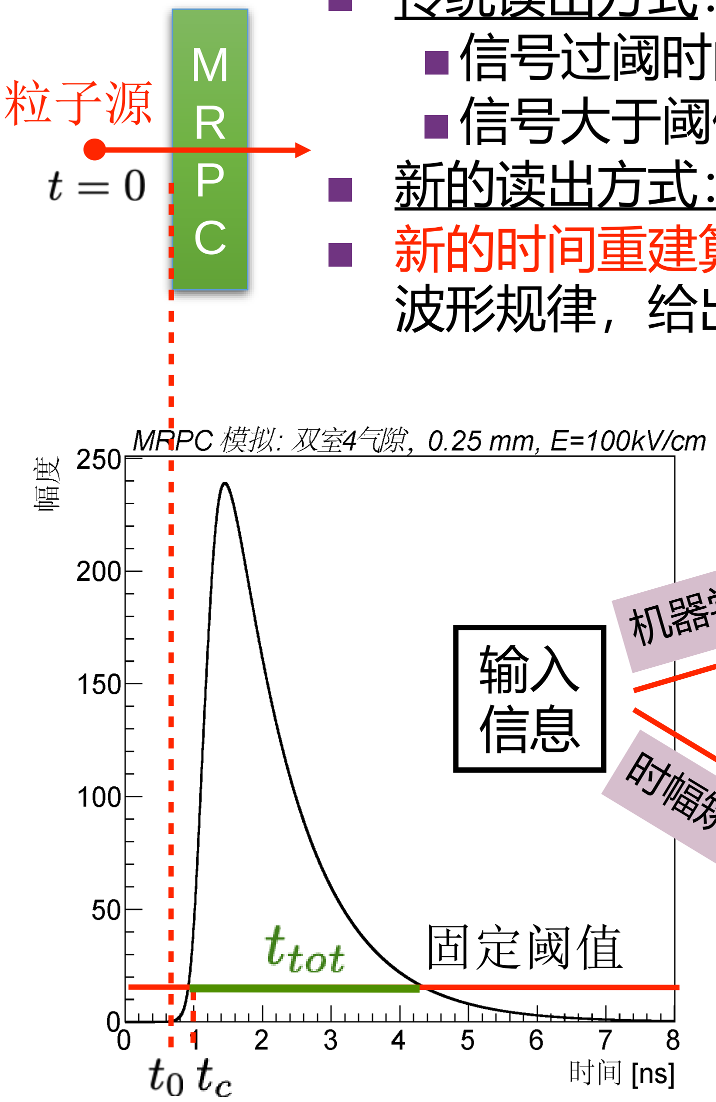
σ_{MRPC} <20 ps， the gas gap: <0.18mm

gap number: >16

基于机器学习的MRPC时间重建算法

- 传统读出方式：设置固定阈值，得到
  - 信号过阈时间：t_c
  - 信号大于阈值的持续时间：t_{tot}
- 新的读出方式：完整信号波形
- 新的时间重建算法：使用神经网络挖掘波形规律，给出粒子飞行时间的估计。





输入信息

机器学习

复杂神经网络结构变化可能性多待定参数众多 → 网络+训练参数 → 多种可能模型

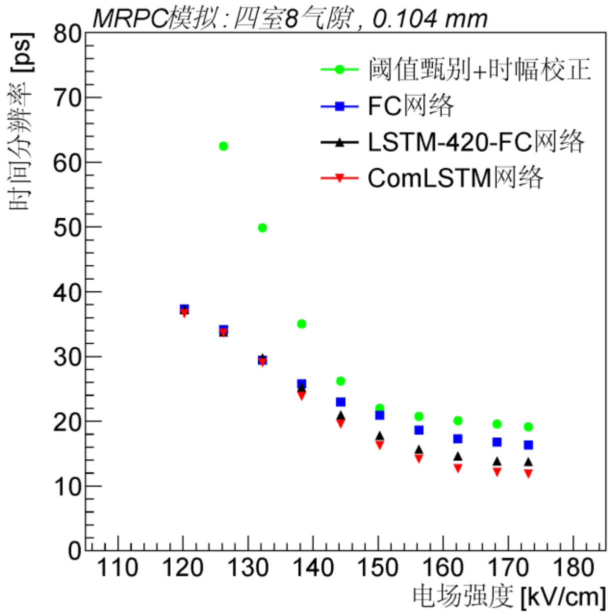
时幅矫正

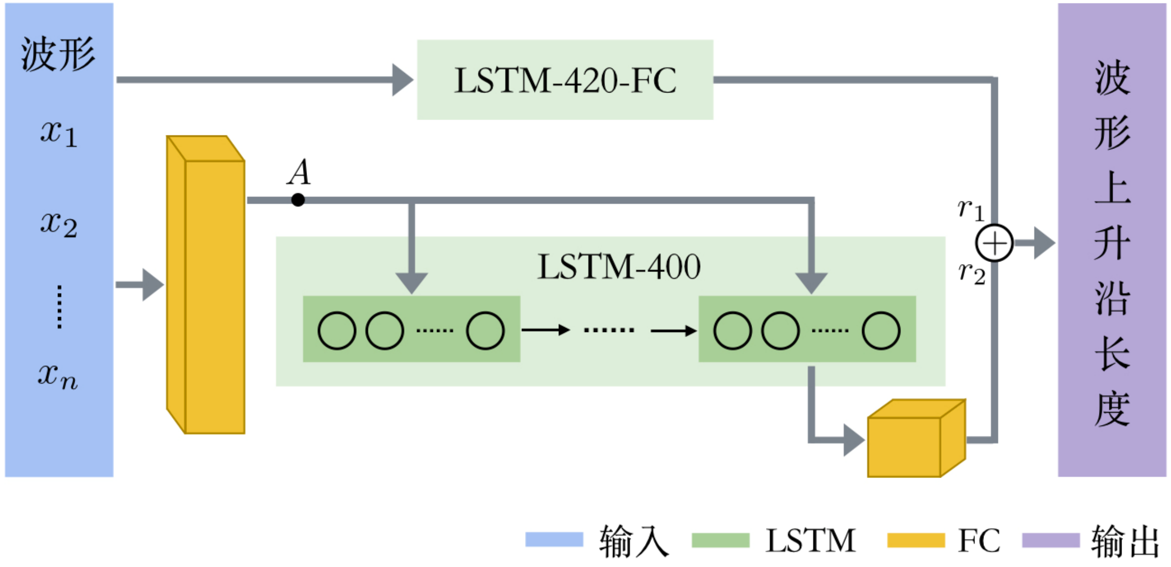
过阈甄别时幅拟合矫正偏差 → 固定的一种数据分析模型

$$t_c = a_0 + \frac{a_1}{\sqrt{T_{tot}}} + \frac{a_2}{T_{tot}} + a_3 T_{tot} + a_4 T_{tot}^2 + a_5 T_{tot}^3$$

改进型comLSTM网络

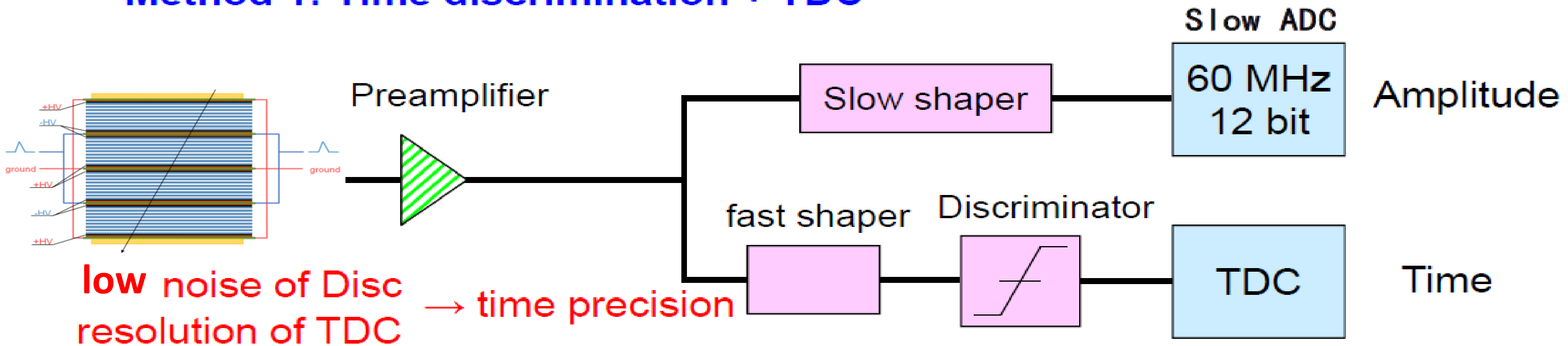
- ComLSTM (Combined LSTM)：结合FC和LSTM，网络的输入分成两路，
  1. 原有LSTM网络（LSTM-420-FC）
  2. 先进入FC扩大输入特征维度，再进入一LSTM-400，提取放大后的细节信息
- 两路输出加权求和后为ComLSTM输出
- 网络训练：6万模拟数据，输入为上升沿上10个点





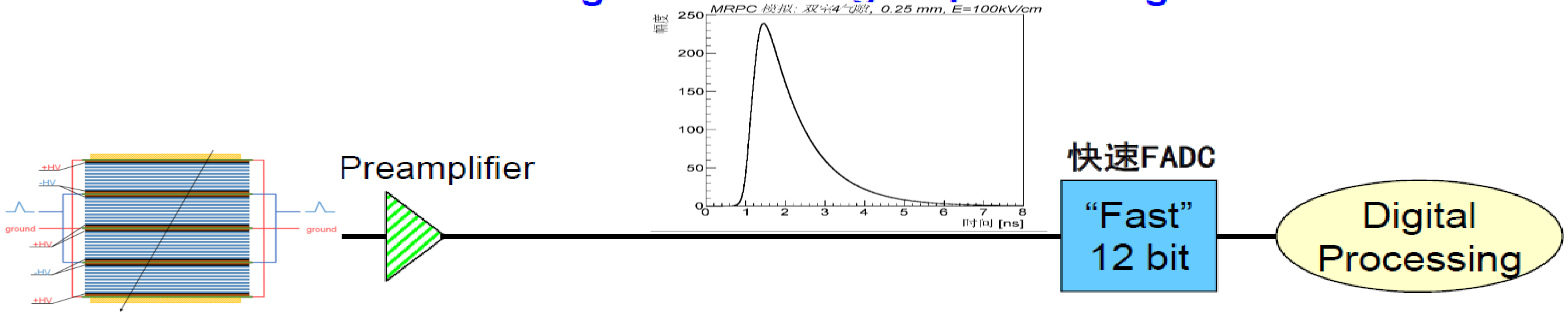
Toward 20ps resolution: fast readout electronics

Method 1: Time discrimination + TDC



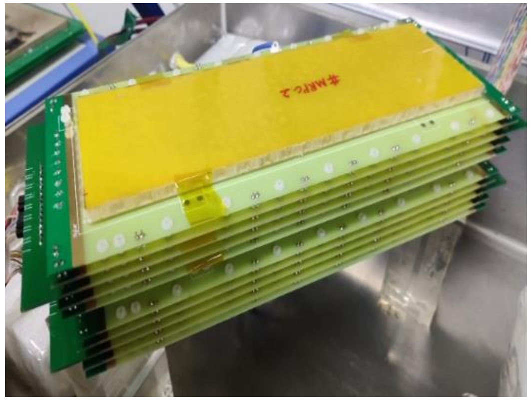
low noise of Disc
resolution of TDC → time precision

Method 2: Waveform digitization + Digital processing



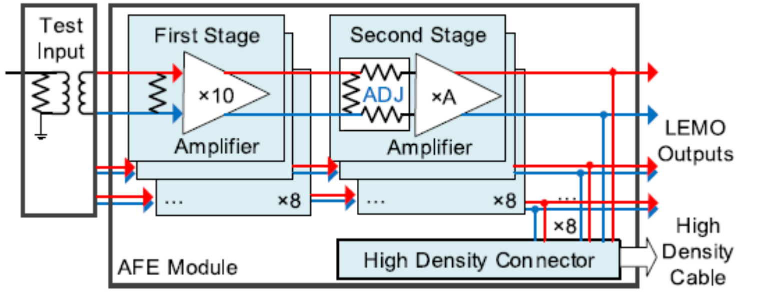
Flash ADC → Power consumption, density, cost
→ Switched Capacitor Array (SCA)

Toward 20ps resolution: fast readout electronics

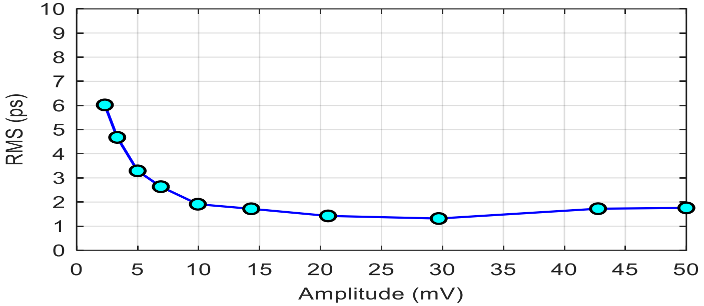


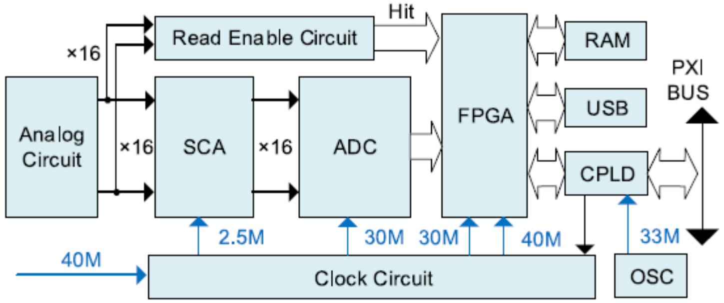
	MRPC prototype
gas gap thickness	128 μm
number of gas gaps	4 chambers × 8 gaps
glass material	**low resistivity glass**
glass thickness	400
readout strips	5 mm in width (2 mm clearance)

材料厚度：<0.1X_0

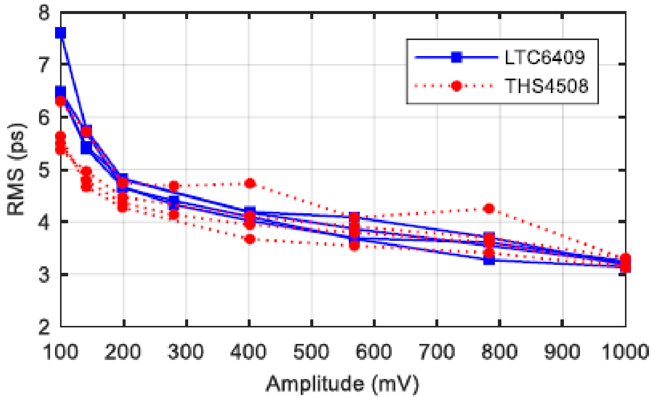


Fast amplifier
Bandwidth=1.4GHz





Waveform sampling
Based on DRS4
Sampling freq=5 GS/s

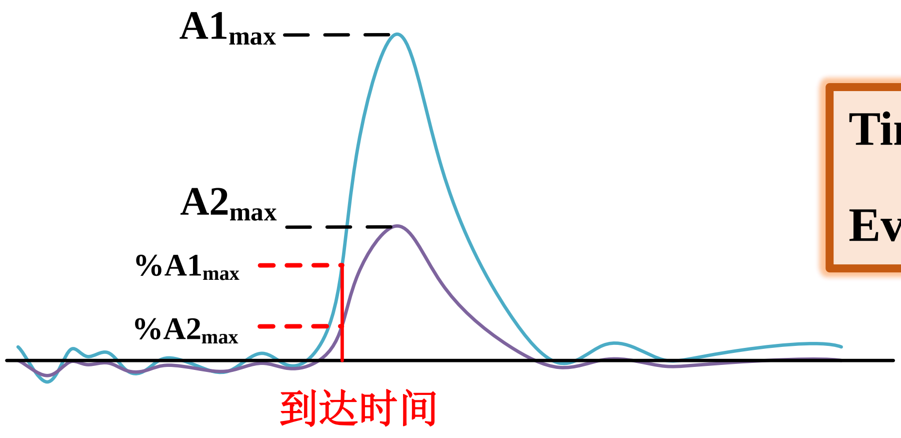


- Fast amplifier & Waveform sampling

Electronic system time σ<7ps

Cosmic test

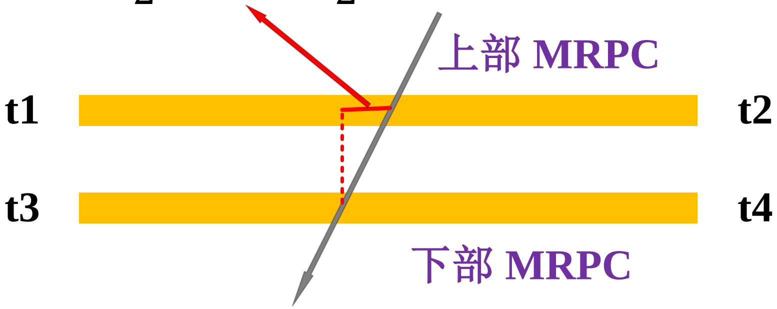
MRPC + fast amplifier + DRS4



Timing: CFD

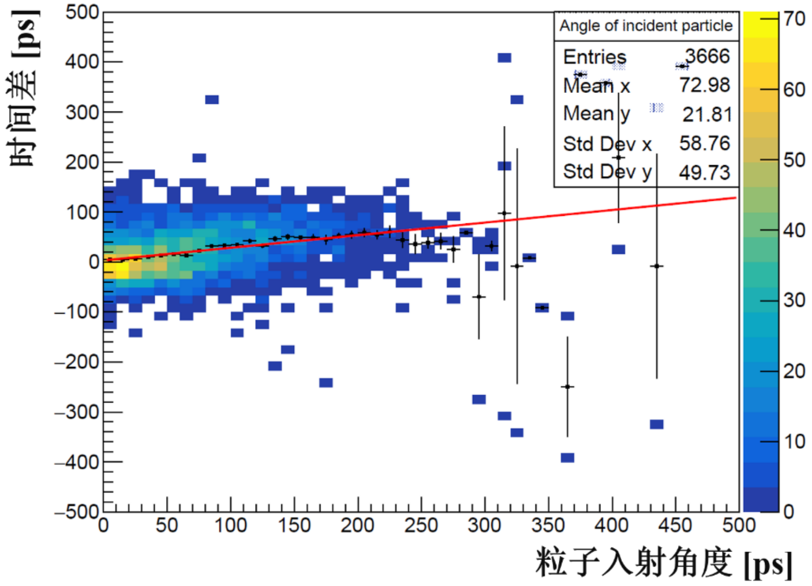
Event choose: Vertical cosmic ray

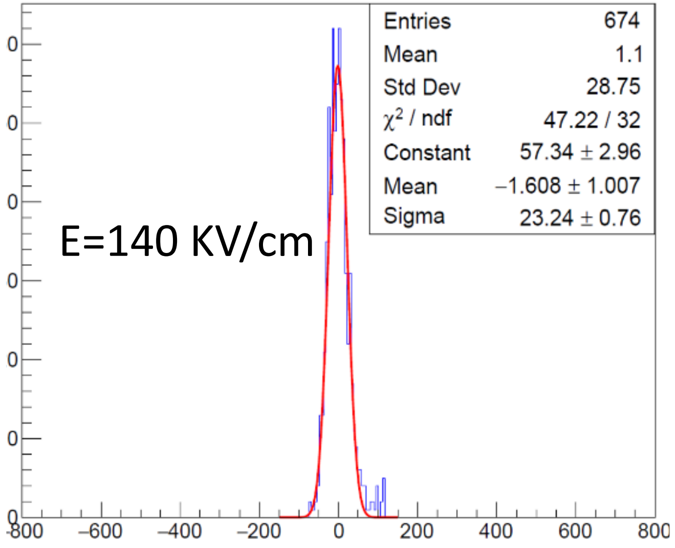
$$cut = \left[\frac{(t1 - t2)}{2} - \frac{t3 - t4}{2}\right] < 3\sigma_{\Delta t}$$



$$\Delta t = (t1 + t2)/2 - (t3 + t4)/2$$

$$\sigma_{MRPC} = \sigma_{\Delta t}/\sqrt{2}$$

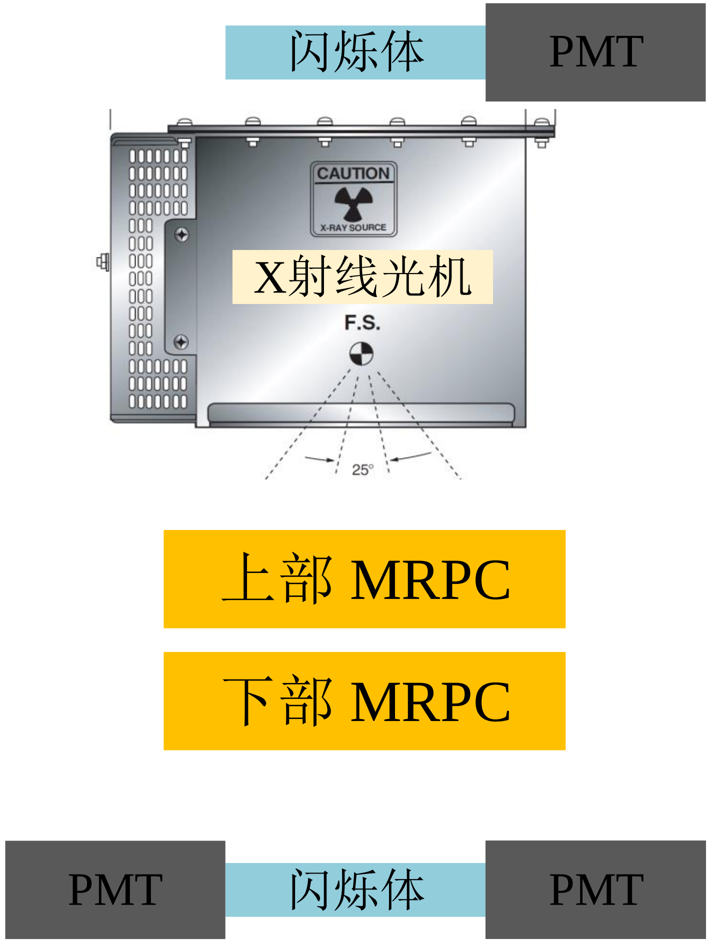


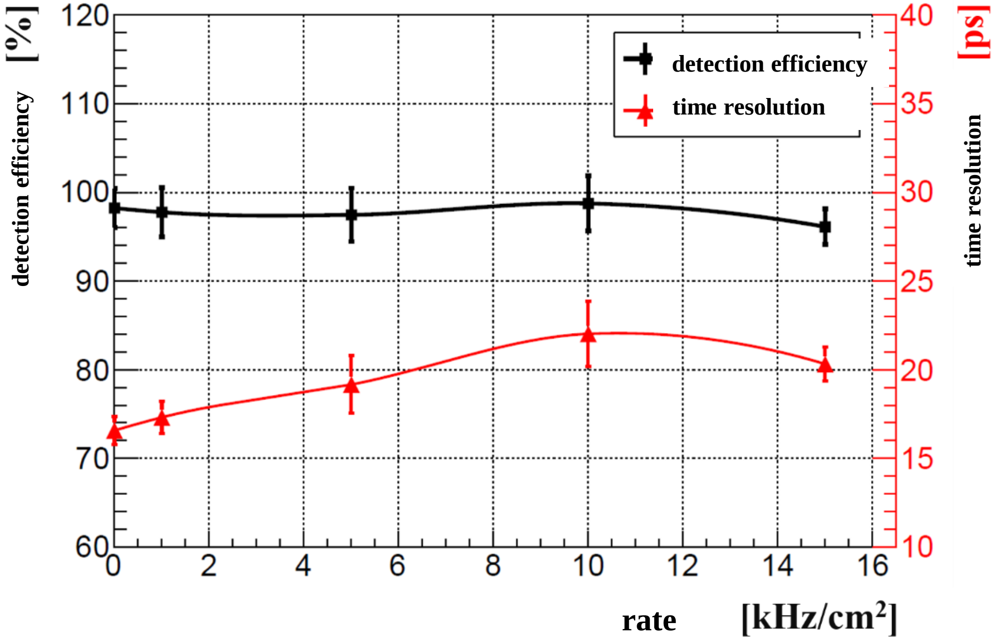


- Total time resolution

$$\sigma = \frac{23.24\text{ps}}{\sqrt{2}} = 16.43\text{ps}$$

20ps,15kHz/cm^2 MRPC





- We are also trying with NINOs+ FPGA TDC to get good resolution!

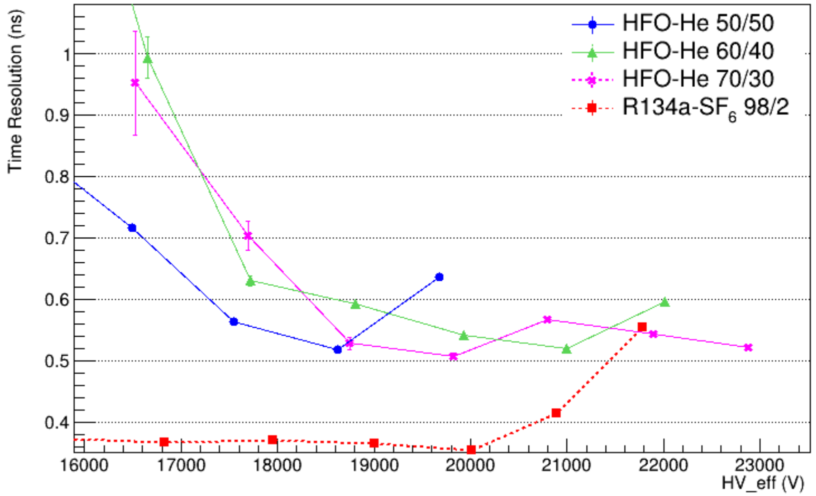
Eco-friendly working gas

- The Global Warming Potential(GWP)

GWP is the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of CO2.

Gas type	GWP
CO2	1
HFC-134a	1430
SF_6	23900
HFO-1234ze	4
He	<1

- Use HFO-He instead of HFC-SF_6
- If HFO-1234ze/He 50/50, GWP=2.5



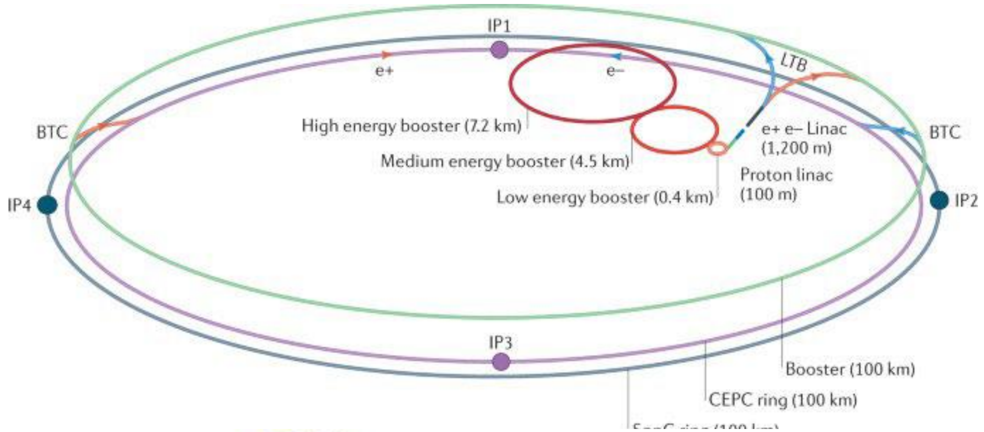
Time resolution of different gas mixture

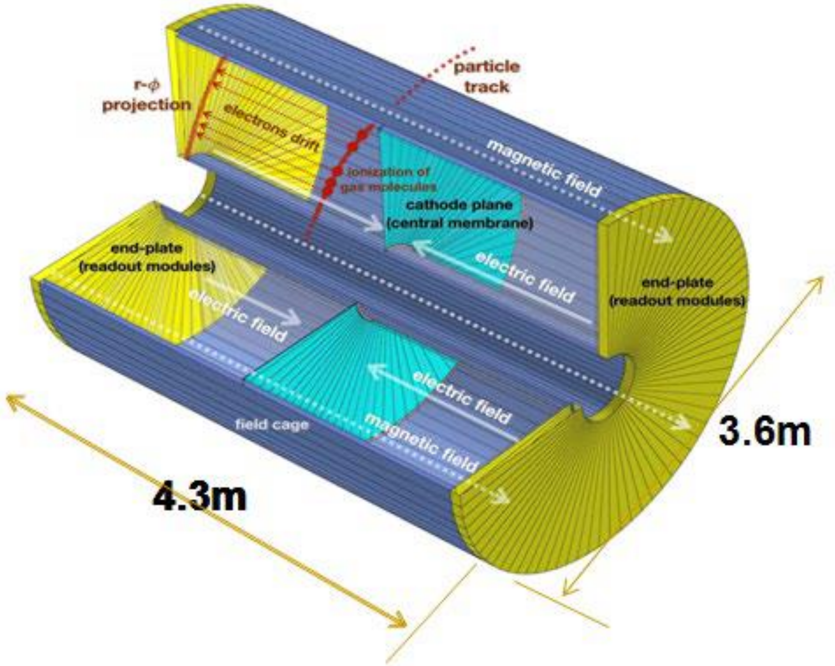
- Disadvantage

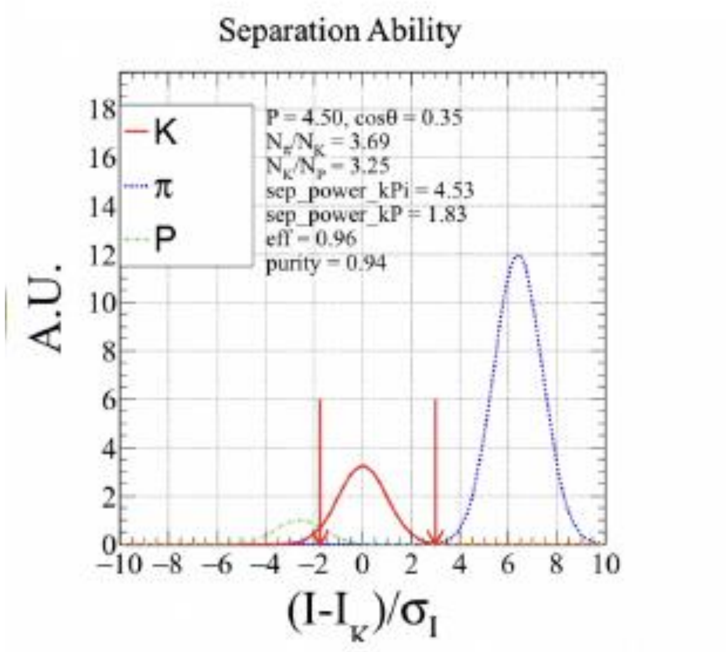
  lower electron drift velocity->worse time resolution
  lower electron drift velocity->bigger culster size
  less quenching->larger streamer fraction

The ecological transition of the EEE experiment, Marcello Abbrescia, Universita e INFN, Bari (IT)
https://indico.cern.ch/event/1123140/contributions/5000797/

PID of CEPC





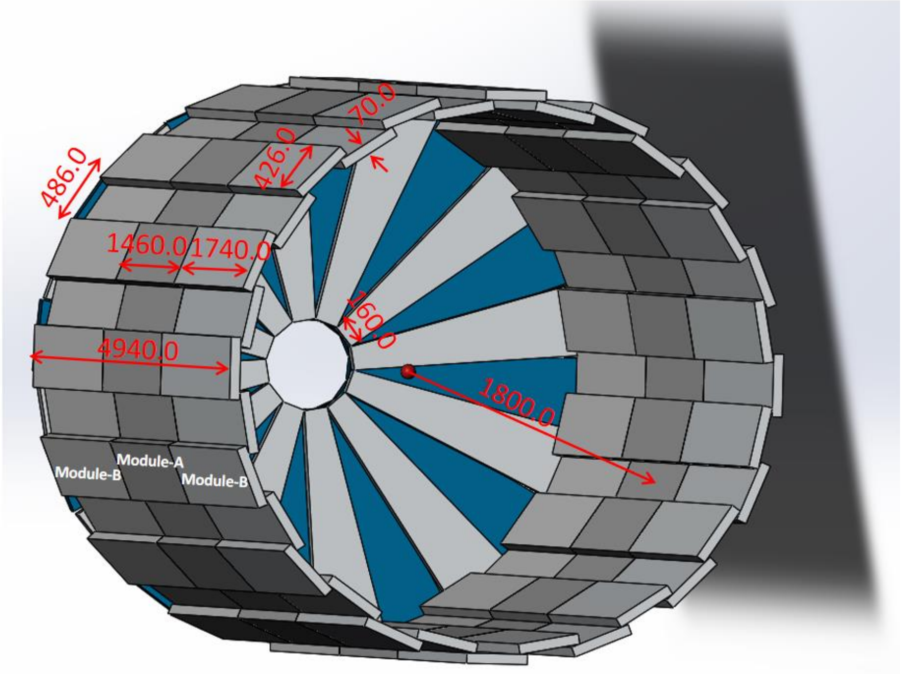


Geant4 simulation:

- TPC resolution: <2.5%
- TOF: <50ps
- PID of K: >98%

From Manqi's summary @ 2022 CEPC workshop

CEPC-TOF总体结构



性能：

1、时间分辨：<35ps

2、PID of π/k: 2.5GeV @3σ

3、TOF面积：~77m^2

4、电子学道数：37632

5、电子学功耗：17mW/道

6、造价估算：3420万RMB (MRPC 784万元)

7、材料厚度：0.1X_0

桶部：

绕筒圆周方向两层tower overlap，每层16个tower，每个tower包含1个module-A和2个module-B，覆盖角度为360°，沿筒轴向放置tower（tower长4.9m）。

Module-A、Module-B中两相邻的MRPC之间2条读出条重叠，读出条为10+2.5mm，4室6气隙单个探测器厚3.02cm。

端部：

一端共24个module，分两层overlap；每个module中有5个探测器，两相邻的MRPC之间1-2条读出条重叠，每个探测器有24个读出条，读出条为10+3.5mm

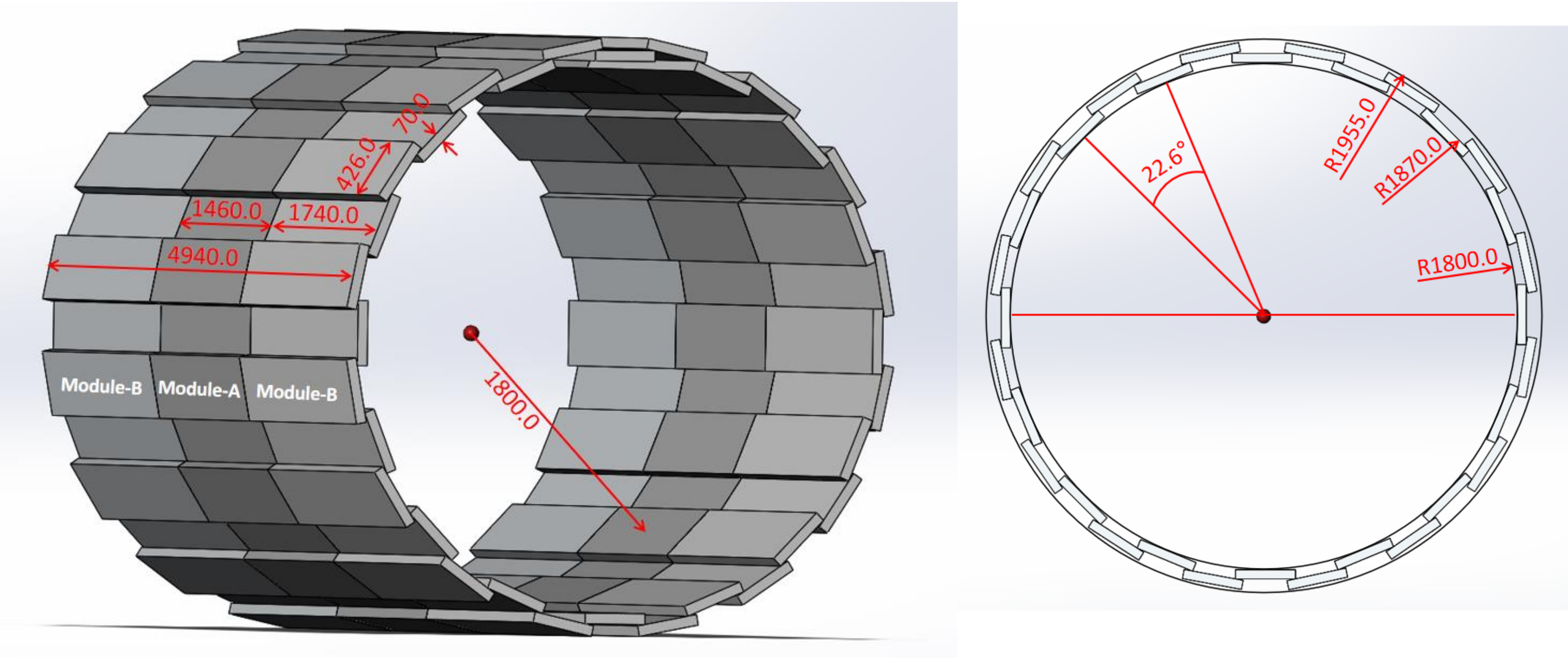


Figure 1.1 Main sizes of the TOF barrel.

MRPC之间的层叠

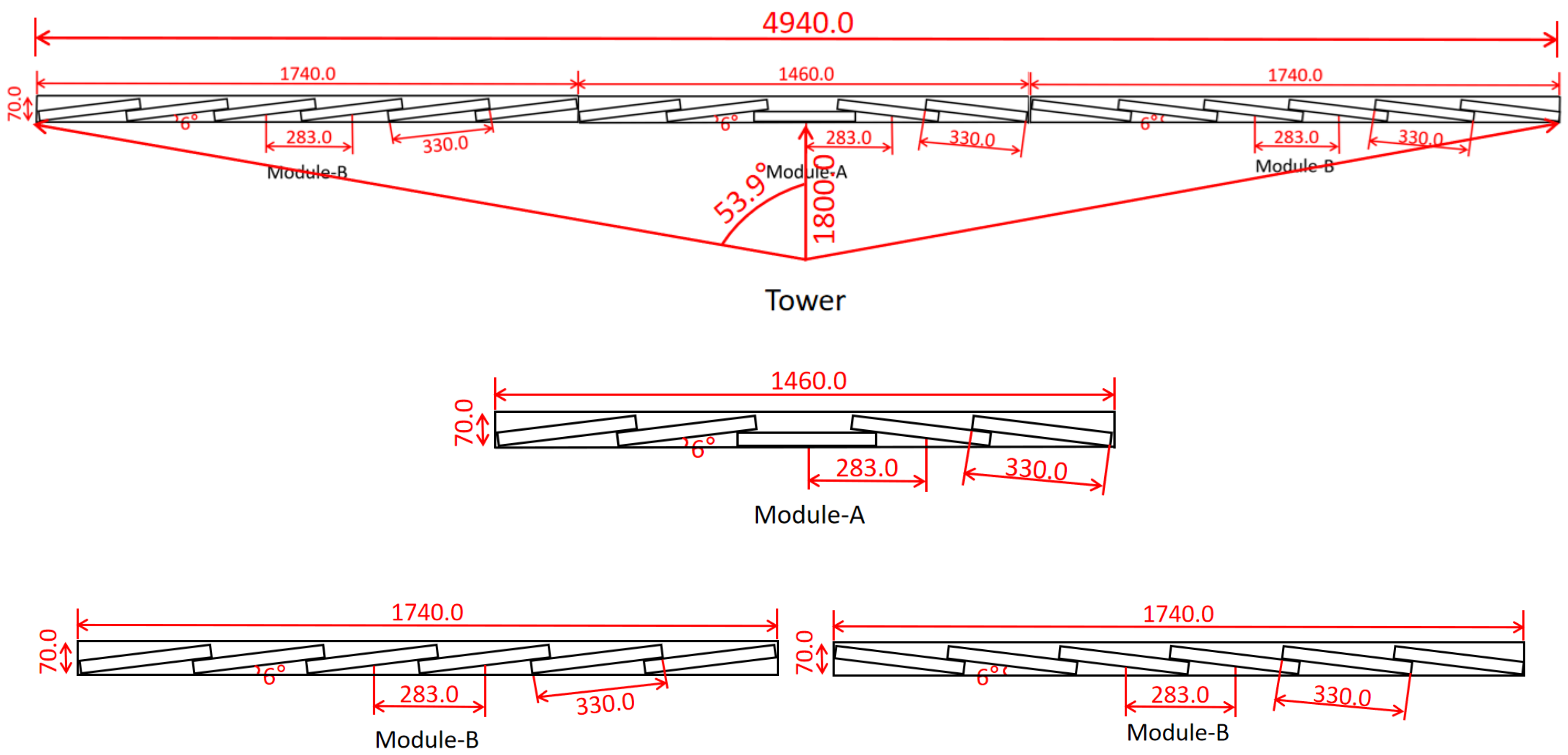


Figure 1.2 Arrangement of MRPCs inside the box along the beam direction.

ETOF的扇形结构

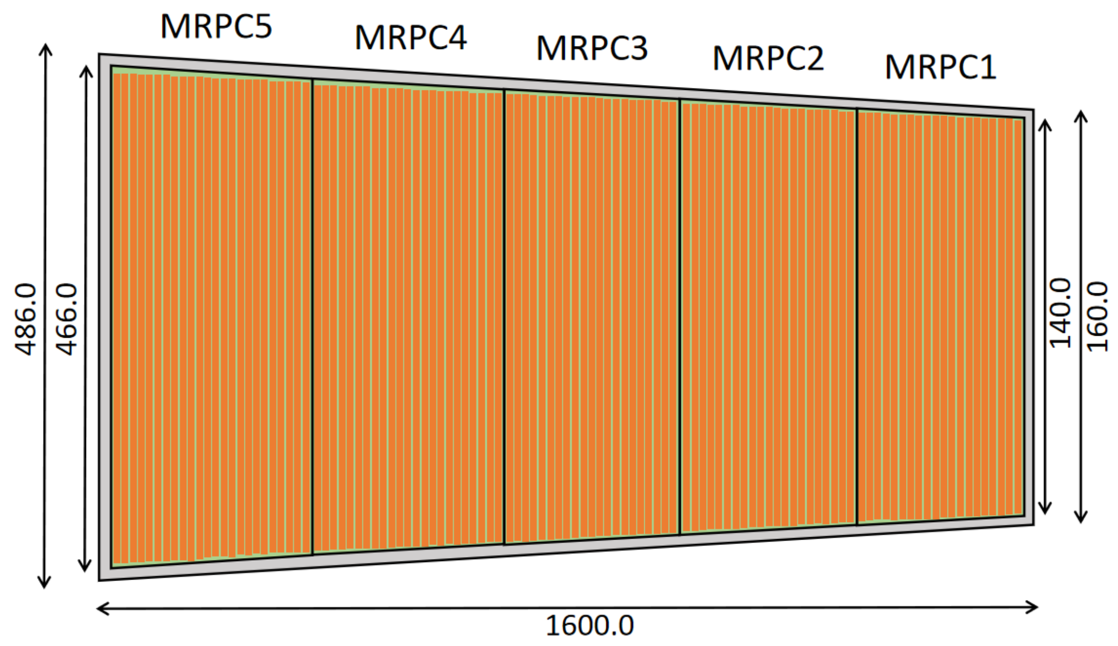


Figure 1.3 Arrangement of MRPCs inside the box in the End-cap.

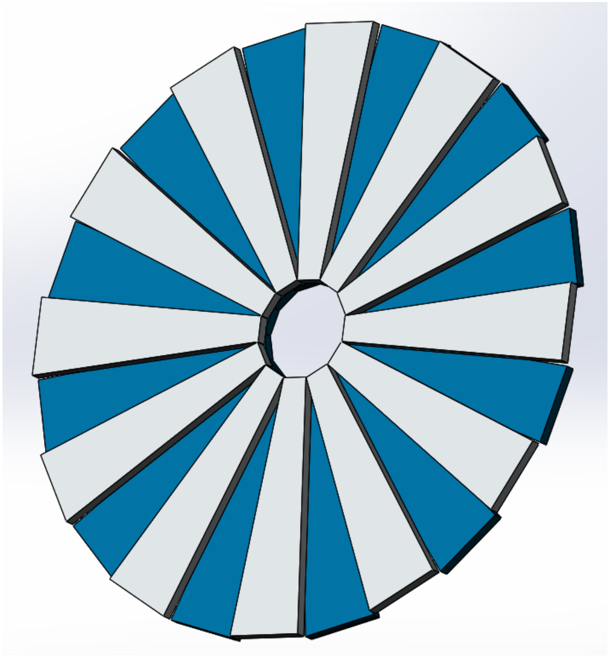


Figure 1.4 Diagram of the End-cap.

电子学通道数

Table 1.1 Main parameters of the TOF system.

		Number of detectors	Number of readout strips	Sensitive area, m^2	Number of FEE cards	Number of FEE channels
Barrel	$MRPC_B$	1	24	0.11	3	48
	Module-A	5	120	0.55	15	240
	Module-B	6	144	0.66	18	288
	Barrel Tower	17	408	1.87	51	816
	$Total_B$	544	13056	59.84	1632	26112
End-cap	$MRPC_E$	1	24	0.07	3	48
	Module-C	5	120	0.35	15	240
	$Total_E$	240	5760	16.80	720	11520
Total		784	18816	76.64	2352	37632

*A barrel tower contains one Module-A and two Module-B.

A conceptual design of TOF based on MRPC technology for the future electron-positron Higgs factory

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Abstract

Future electron-positron Higgs factories, such as CEPC and FCC-ee, will provide unique opportunities to examine the Standard Model and search for new physics with much higher precision than the LHC. To fully exploit the physics potentials of these future colliders, the precise time-of-flight (TOF) measurement is essential. In this paper, we propose a conceptual design of TOF system based on the multigap resistive plate chamber (MRPC) technology for future electron-positron Higgs factories. It is anticipated to achieve a time resolution of less than 35 ps. The total cost of the whole TOF system is estimated to below 35 million RMB.

Keywords: MRPC, ToF, PID, CEPC

JINST manuscript

文章已被JINST接收发表！

Summary

- The rate capability of MRPC assembled with low resistive glass can reach 70kHz/cm^2
- Sealed MRPC was developed in our university:

  -- Promote gas exchange in gas gap

  -- Sealed MRPC (fishing line spacer) can work well under 7kHz/cm^2 condition

  -- Sealed MRPC (Mylar pad spacer) can solve creepage on the spacer at high rate condition (>7kHz/cm^2)

  -- Reduce gas consumption greatly

  -- Has been used in CBM-TOF and CEE-eTOF
- The time resolution of **narrow gap MRPC with fast electronics** can be better than 20ps

Thanks for your attention！