Status of Technology of MRPC time of flight system

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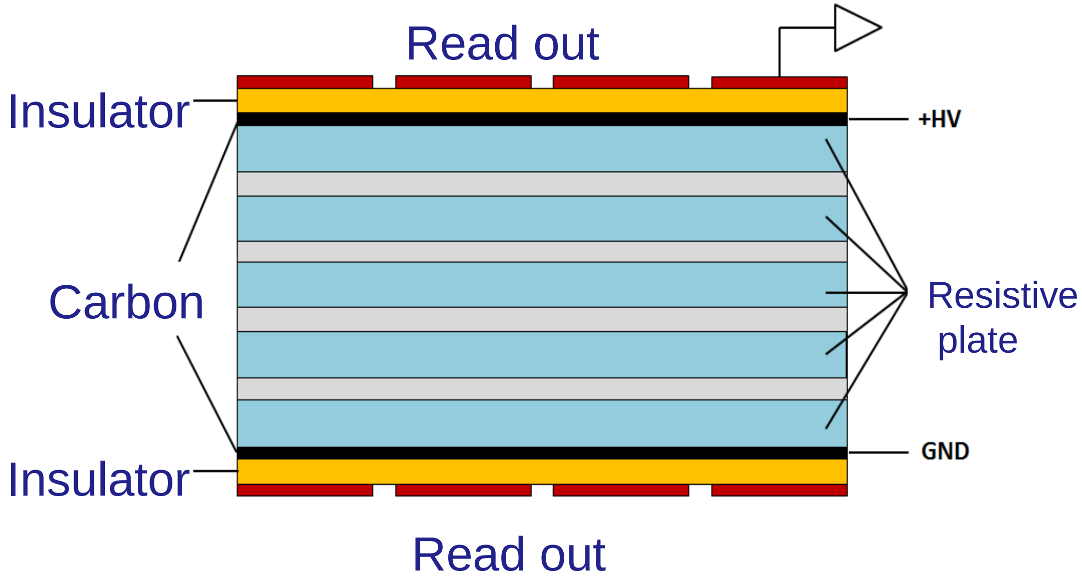
Abstract:

- Introduction of MRPC
- Introduction of three generation MRPC TOF
- Status of TOF of STAR, CBM and SoLID
- Conclusion

MRPC introduction



MRPC structure

Standard parameters:

- Resistivity of glass: ~10^{12} Ω.cm
- Working gas: 90%Freon+5%iso-butane+5% SF6
- **Time resolution <100ps**
- Efficiency >95%
- Charge: a few PC
- Dark current: a few nA
- Noise ~1Hz/cm^2
- Rate <100 Hz/cm^2
- Large area, low cost

MRPC application：

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

How to increase rate of MRPC

The voltage drop in the gas gap:

$$\bar{V}_{drop} = V_{ap} - \bar{V}_{gap} = \bar{I}R = \bar{q}\phi\rho d$$

The smaller the voltage drop, the higher efficiency and higher rate capability!

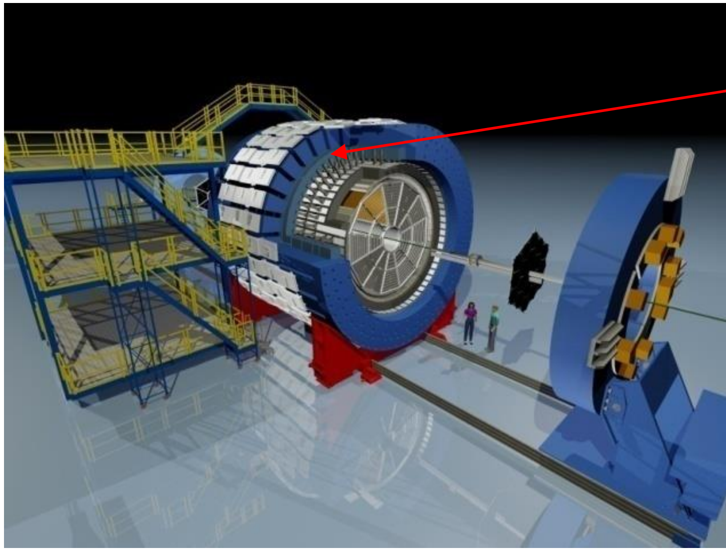
Two main ways to improve rate capability:

- Reducing bulky resistivity of electrode glass (CBM)
- Reducing the avalanche charge (ATLAS)

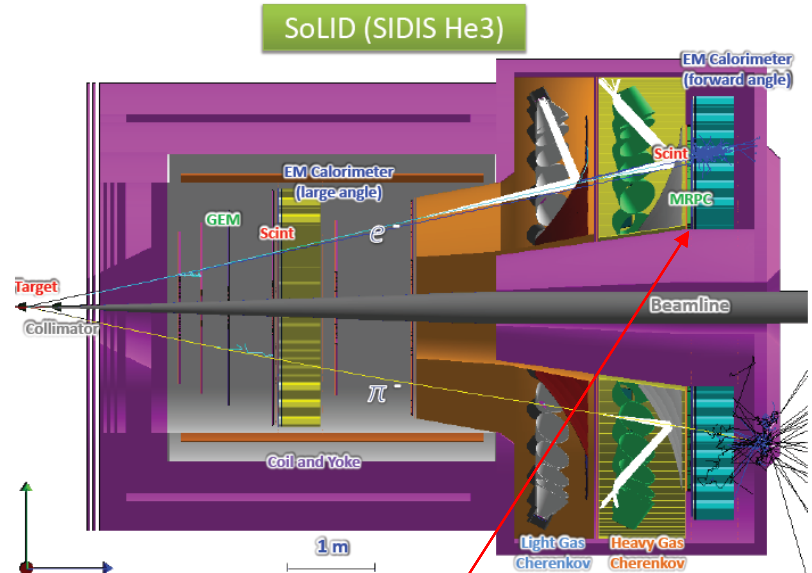
Other methods:

- Reducing the thickness of glass
- Warming the detector

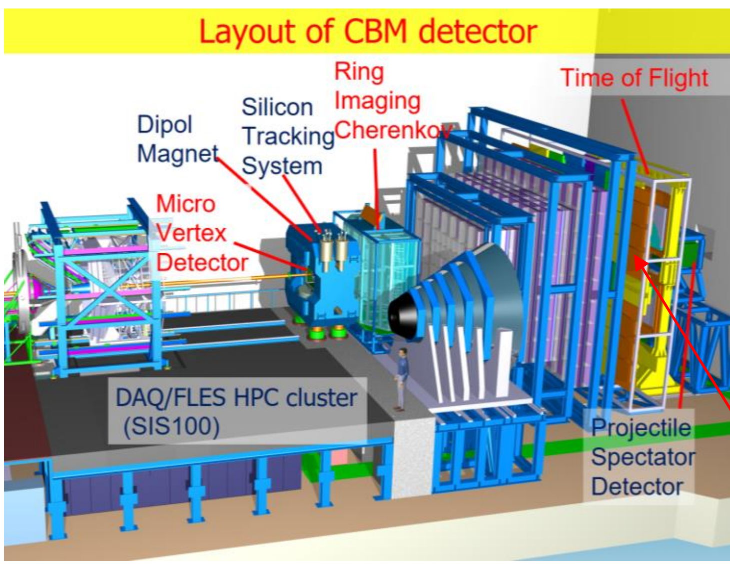
Typical MRPC TOF



RHIC-STAR TOF
Float glass



JLab-SoLID TOF
High rate and 20ps resolution



FAIR-CBM TOF
High rate- low resistive glass

Key technology

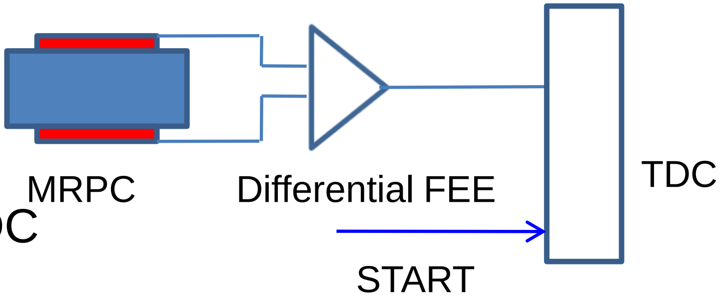
1^{st} generation TOF (from 2000):

Requirement: Time resolution: <80ps

Rate : <1kHz/cm²

Technology: common glass MRPC+NINOs +HPTDC

Analysis method: TOT slewing correction



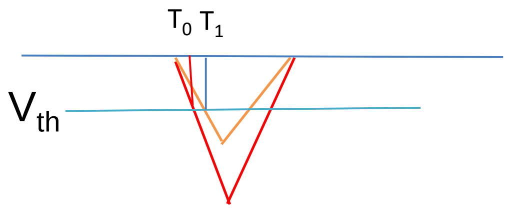
2^{st} generation TOF (from 2008):

Requirement: Time resolution: <80ps

Rate : 30kHz/cm²

Technology: low resistive glass MRPC+PADI +GET4

Analysis method: TOT slewing correction



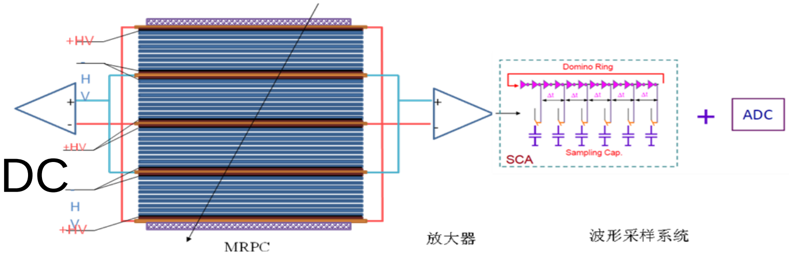
3^{st} generation TOF (from 2012):

Requirement: Time resolution: <20ps

Rate : 20kHz/cm²

Technology: low resistive glass MRPC+SCA +ADC

Analysis method: TOT slewing correction



Deep learning+ Neural network

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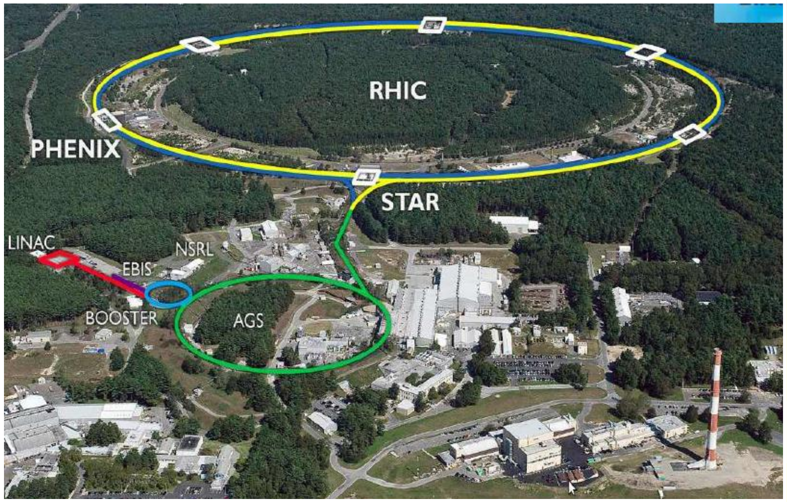
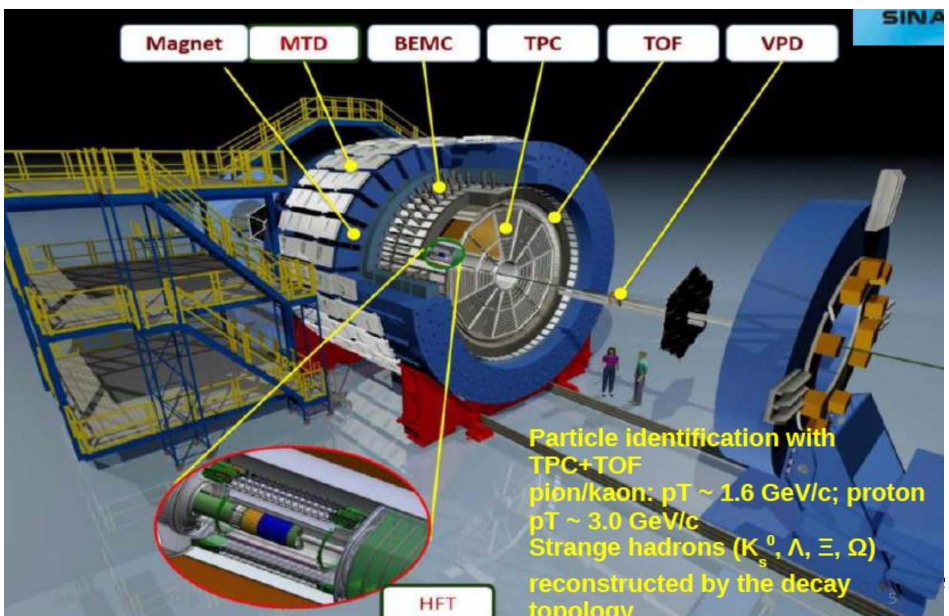
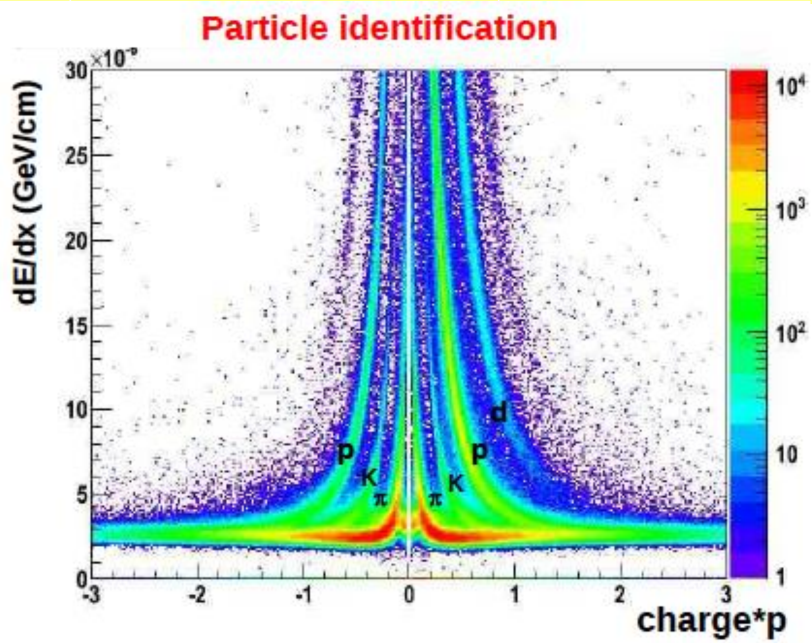
RHIC-STAR

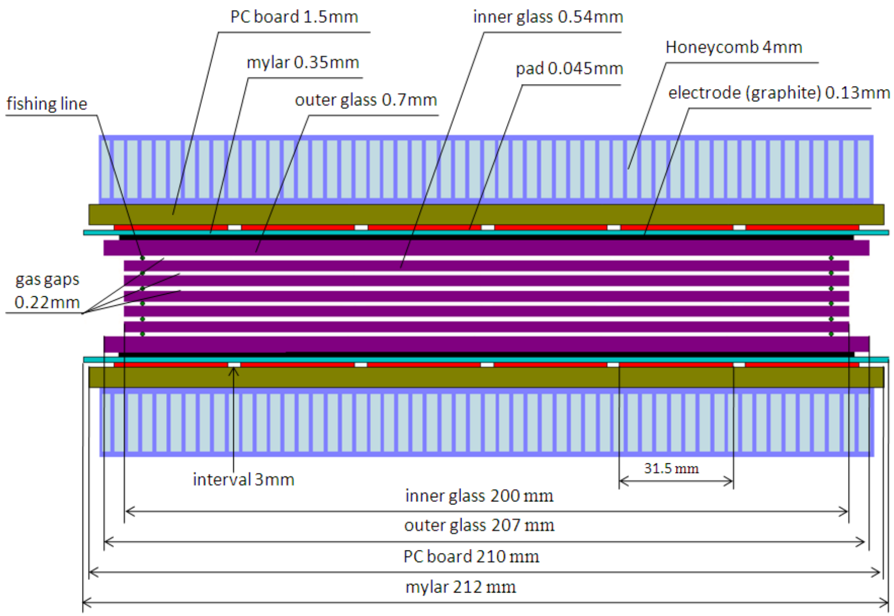


Collision species	C.M. Energy per nucleon pair (GeV)	Physics
Polarized p+p	510, 200, 150	Spin physics
Au+Au	200, 130, 62.4, 39, 27, 19.6, 14.5, 11, 7.7	Quark Gluon Plasma properties, QCD Critical point search
Cu+Cu, Cu+Au	200, 62.4, 19.6, 22.4	Study initial conditions
d+Au	200	Cold nuclear matter
U+U	193	Study initial conditions

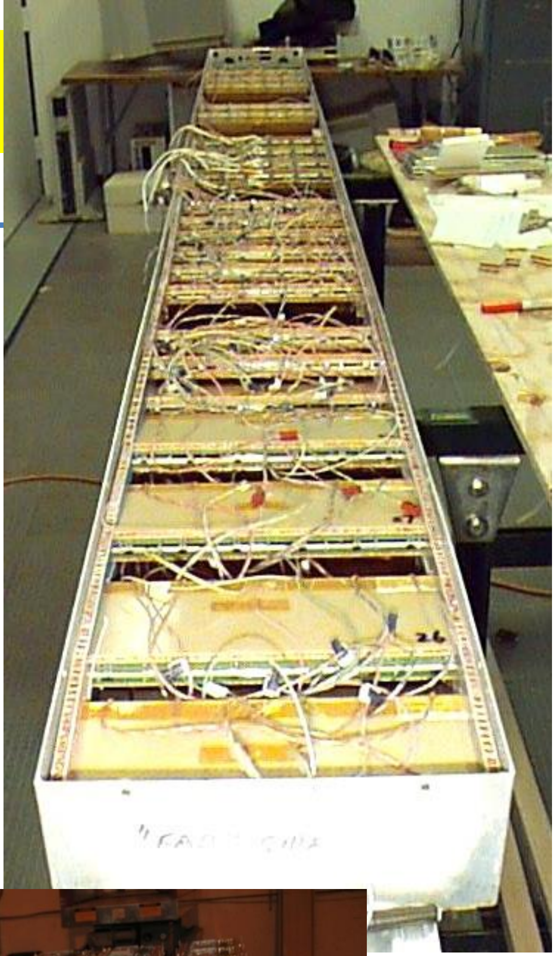


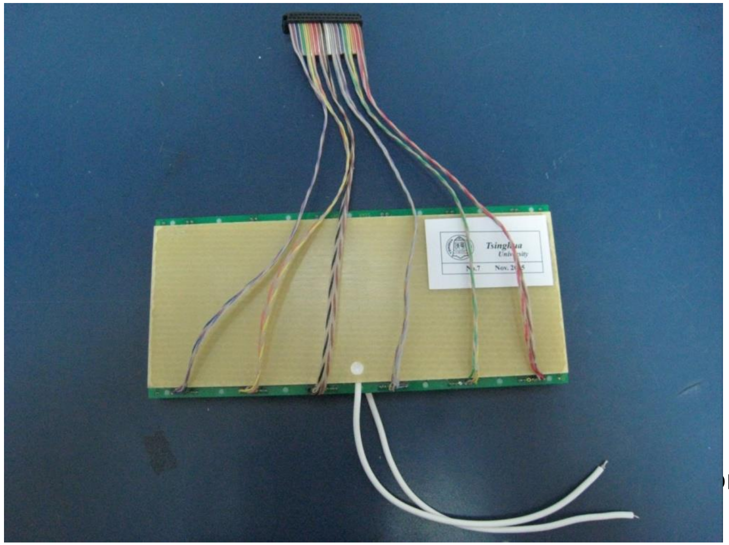


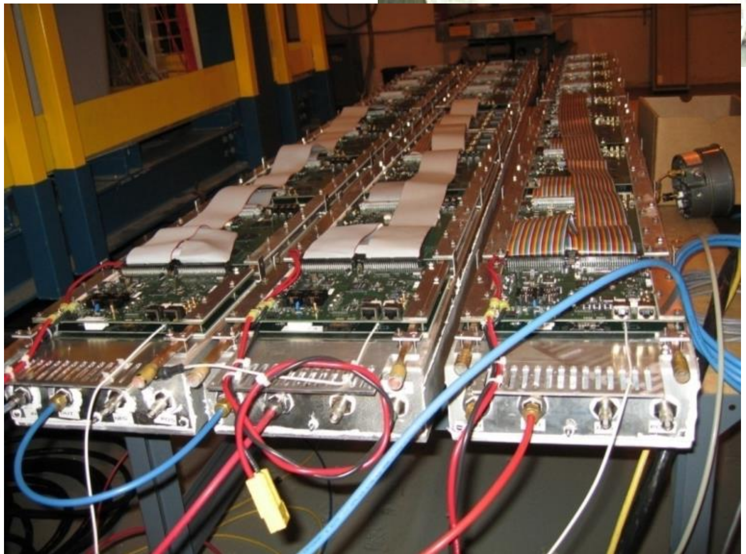
STAR-TOF MRPC



Long side view

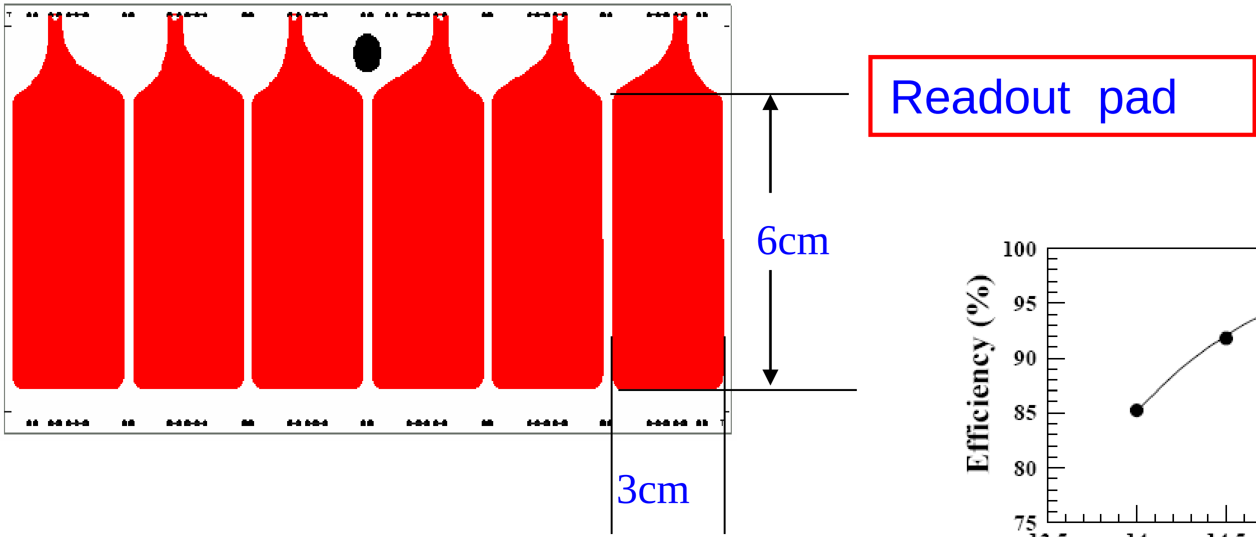


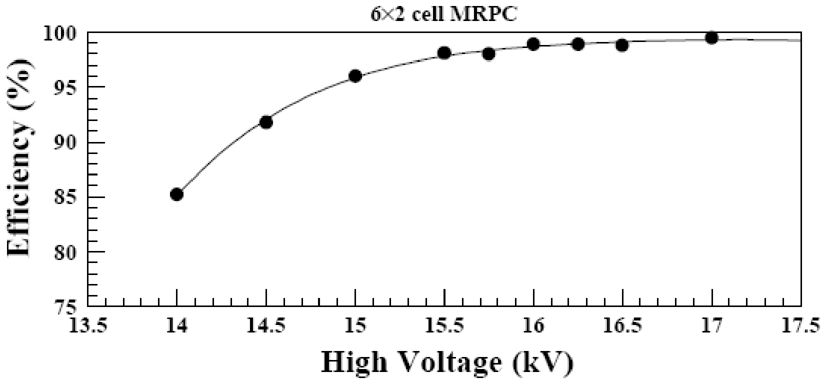


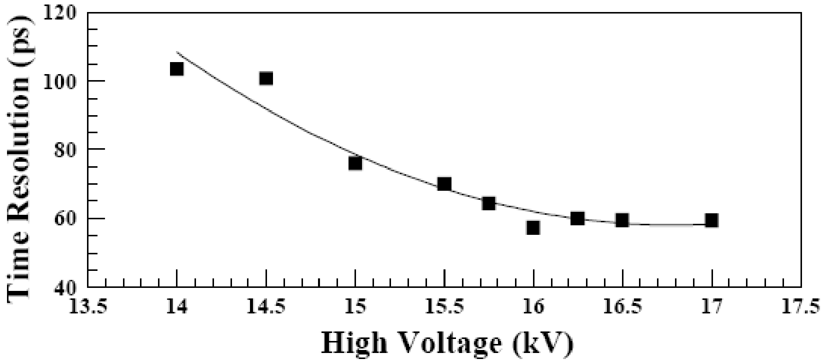


n the high

STAR MRPC performance

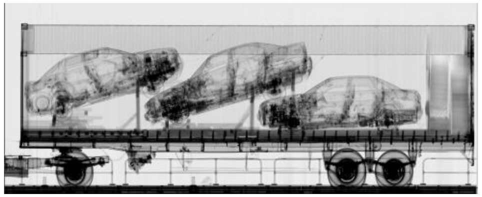




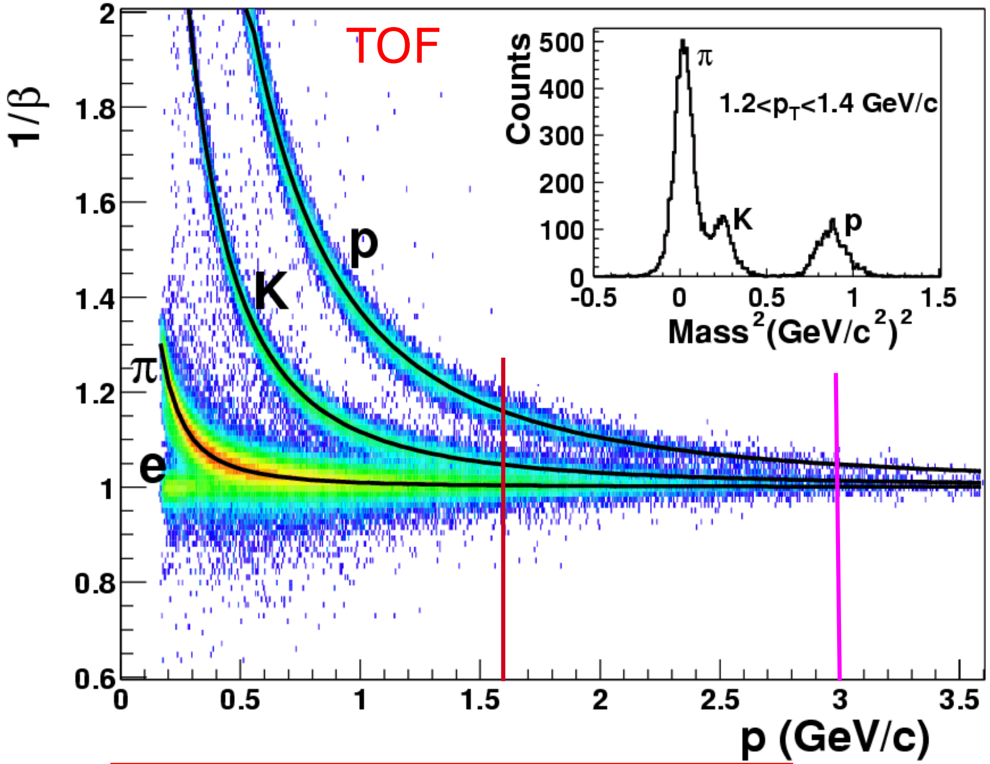


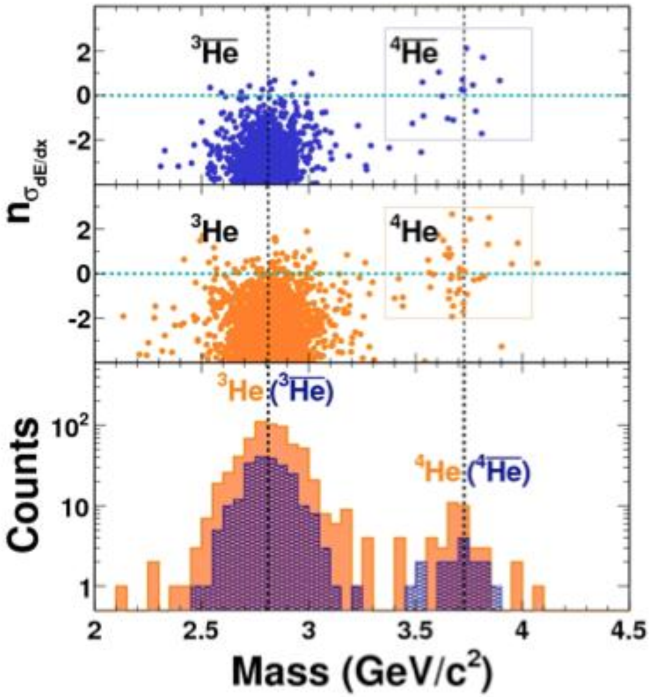
Glass: ~$4\times10^{12}\Omega$.cm
Carbon tape: 500k Ω/□
Gas gap: 6×0.22mm
Working gas: 95% F134a+5% iso-butane
Time resolution: 70ps
Efficiency >90%
Rates capability: <500Hz/cm^2 !

MRPC mass production



PID of STAR-TOF





TOF PID:

π /k ~1.6 GeV/c,

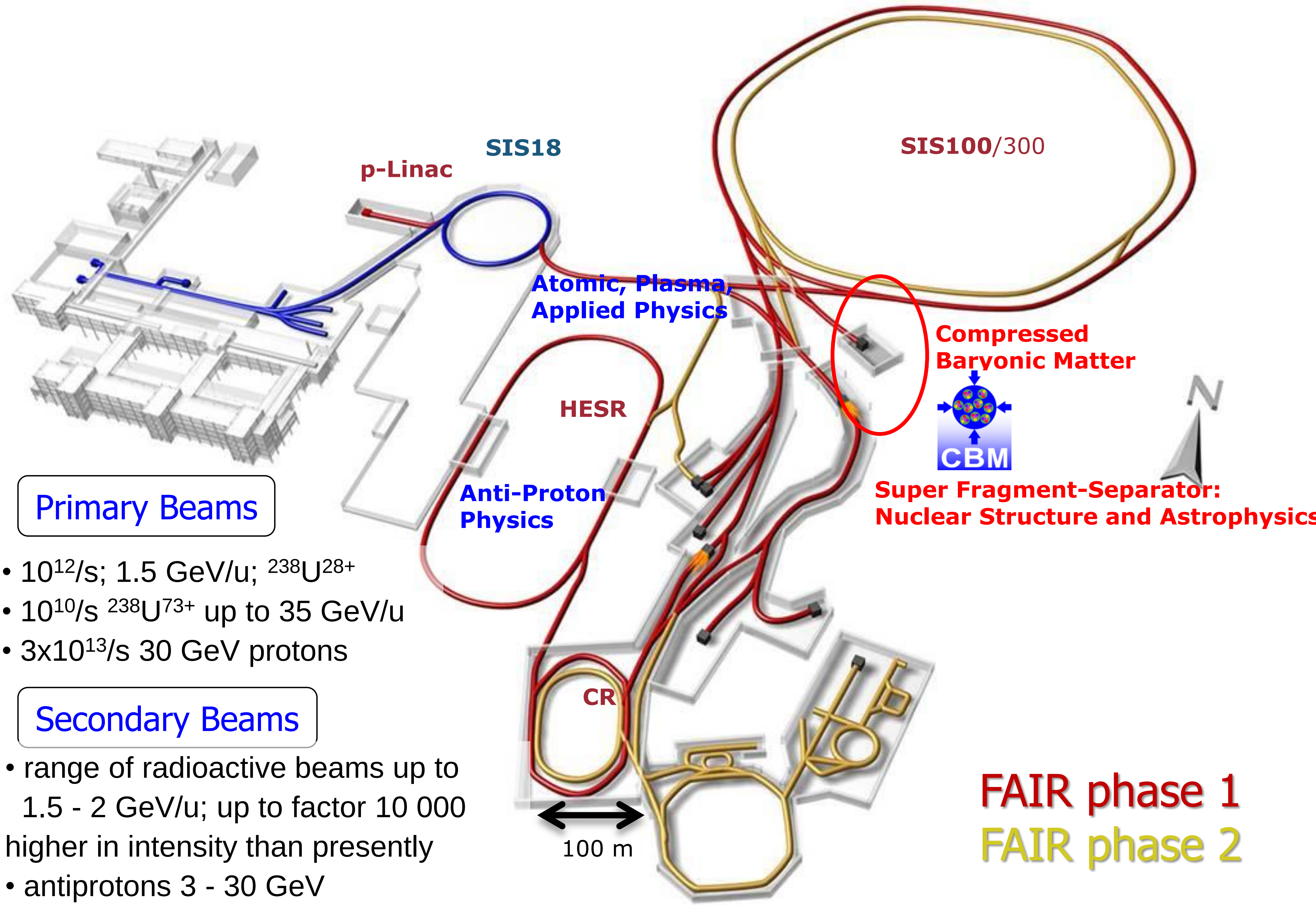
(π,k)/p ~ 3.0 GeV/c

Observation of the antimatter helium-4 nucleus

The STAR Collaboration*

Nature 473 (2011) 353

Facility for Antiproton and Ion Research



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- $3x10^{13}$/s 30 GeV protons

Secondary Beams

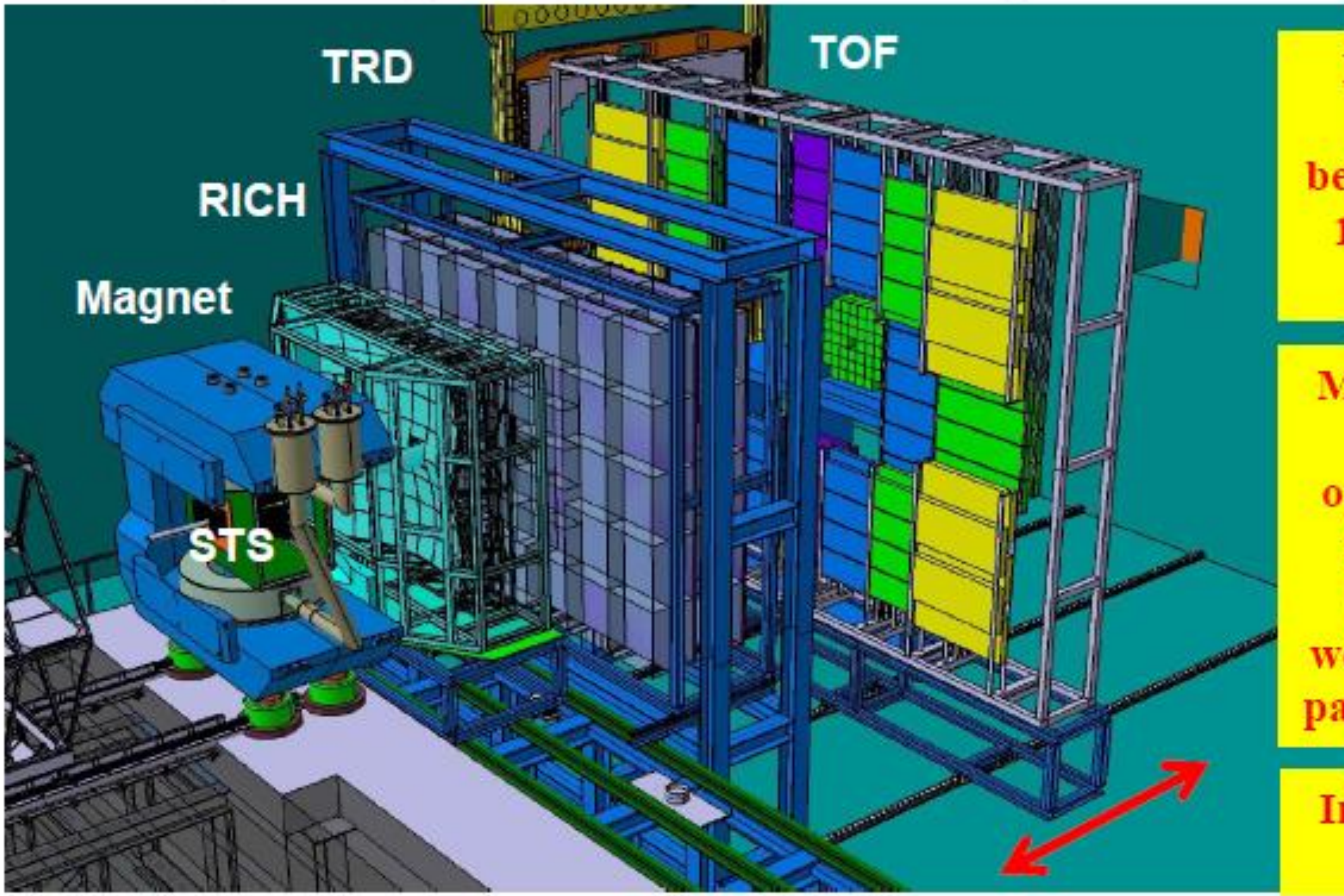
- range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

FAIR phase 1

FAIR phase 2

Layout of CBM detector

Engineering design of the CBM experiment



Nominal ToF position is between 6 m and 10 m from the target

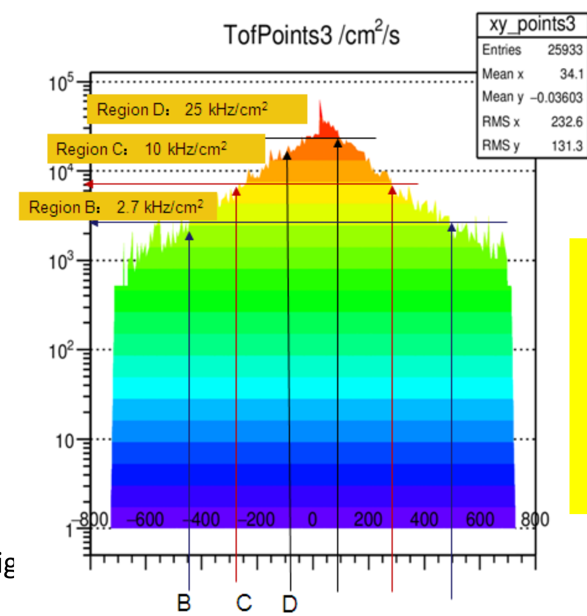
Movable design allows for optimization of the detection efficiency of weakly decaying particles (Kaons)

Interaction rate 10 MHz

The structure of CBM-TOF wall

CBM-ToF Requirements

- Full system time resolution σ_T ~ 80 ps
- Efficiency > 95 %
- Rate capability ≤ 30 kHz/cm^2
- Polar angular range 2.5° – 25°
- Occupancy < 5 %
- Low power electronics (~100.000 channels)
- Free streaming data acquisition

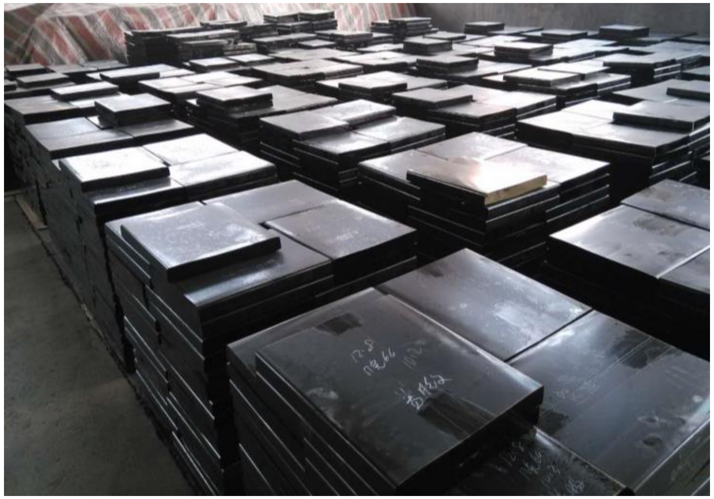


Au+Au, Center, 10AGeV Simulated with CBM ROOT

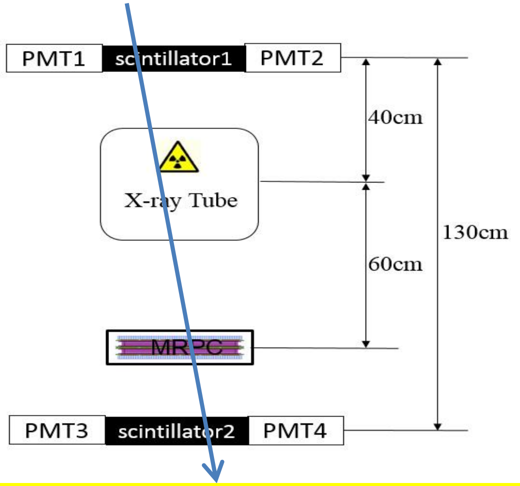
Development of low resistive glass

Performance of the glass

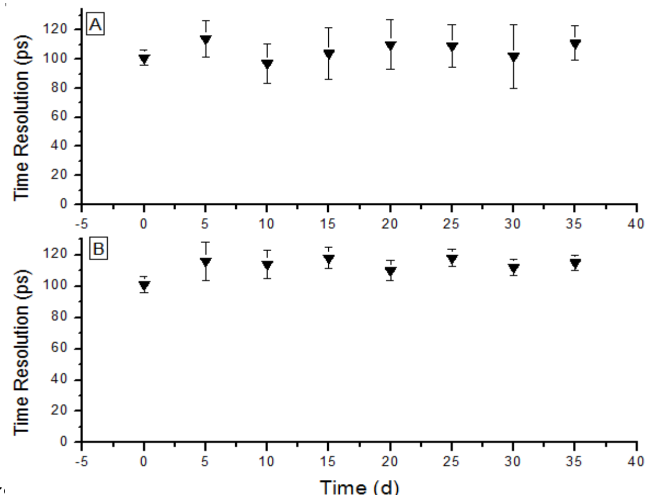
Maximal dimension	32cm × 30cm
Bulk resistivity	10^{10} Ωcm
Standard thickness	0.7, 1.1mm
Thickness uniformity	20 μm
Surface roughness	< 10nm
Dielectric constant	7.5 - 9.5
DC measurement	Ohmic bebavior stable up to 1 C/cm^2



Glass mass production
Yield >100m^2/month

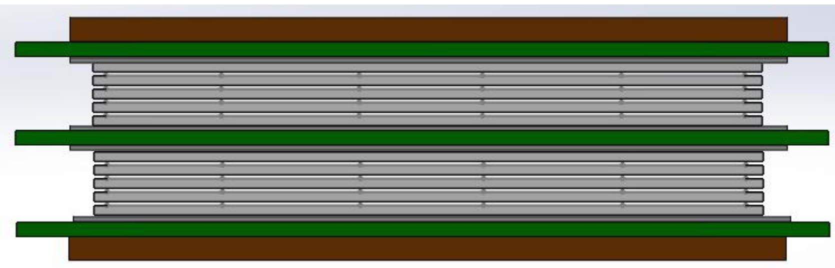


Aging test with X-ray source



Online test system. The efficiency and time resolution can be obtained by cosmic ray while irradiated by X-rays. 0.1C/cm^2 charge is accumulated in 35 days.

Design of strip-MRPC for high rate region

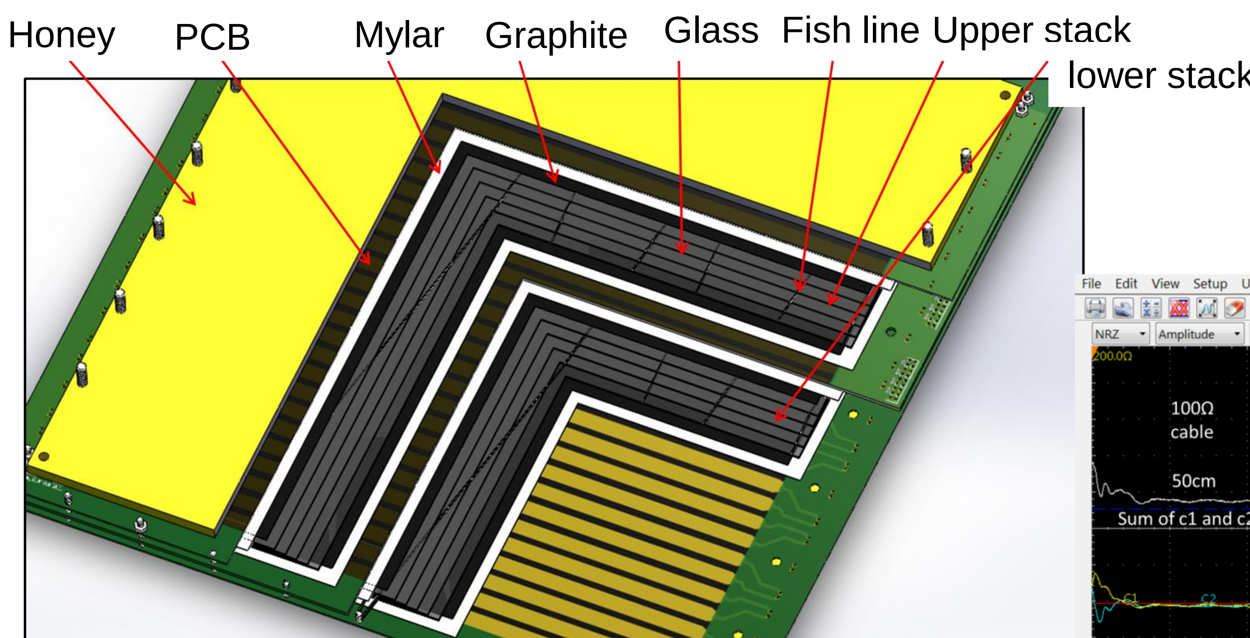


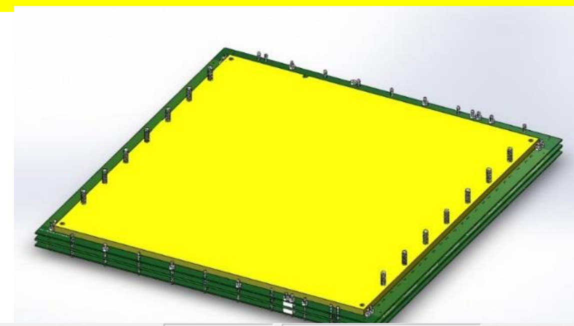
Glass: low resistive glass

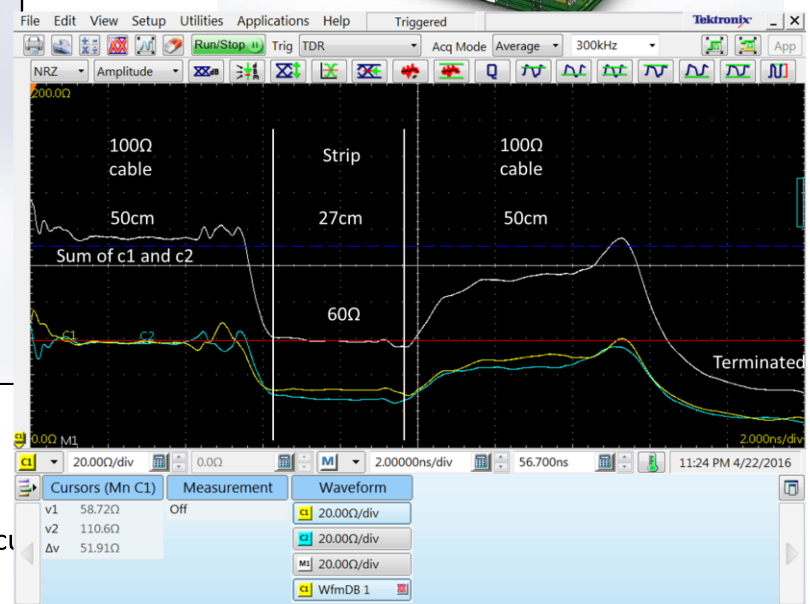
0.7mm thick, 33cm x 27.6cm

Strip: 27cm x 0.7cm, 0.3cm interval, 32 strips

Gas gap: 8 x 0.25mm, two stacks

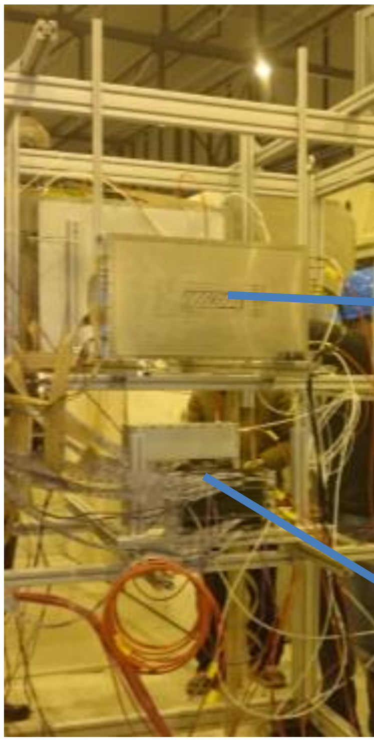






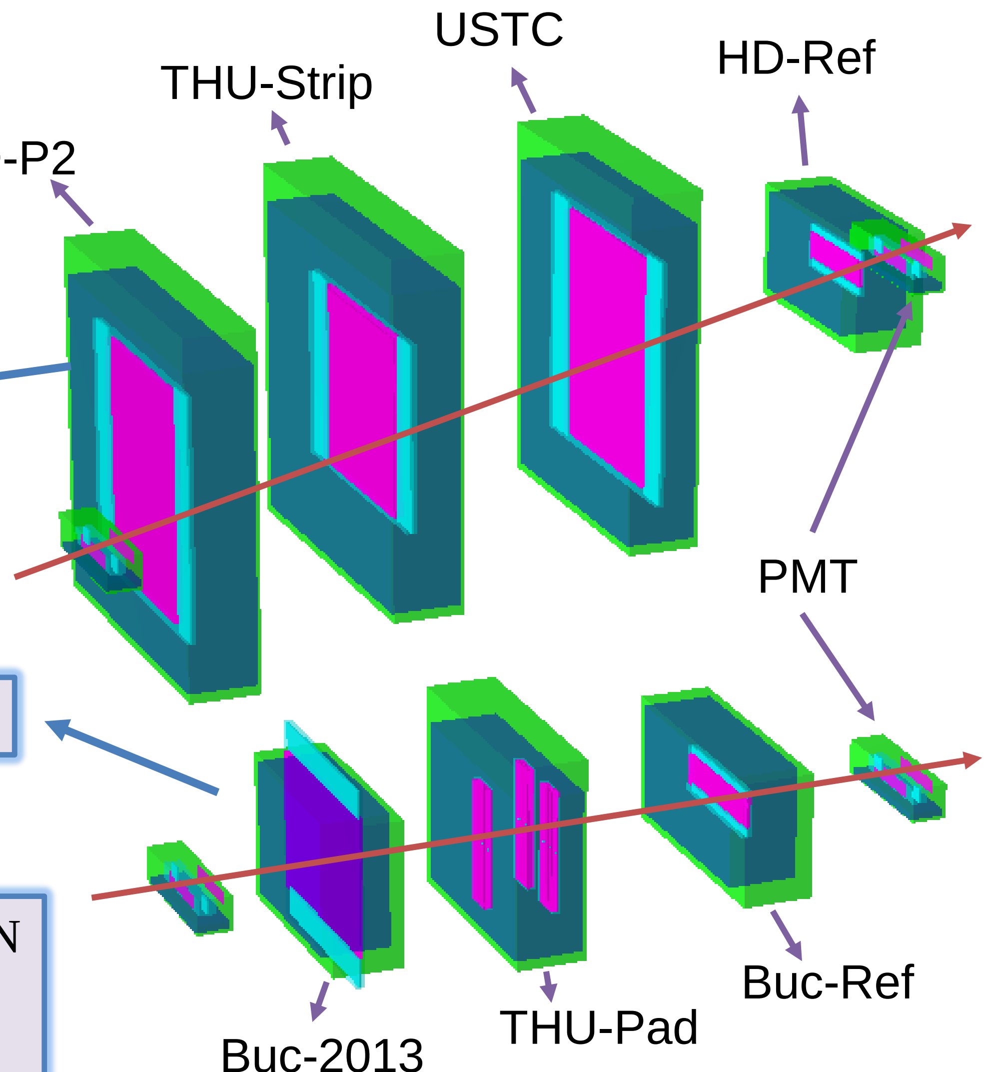
Beam test @ SPS Feb 2015

Experimental Setup:



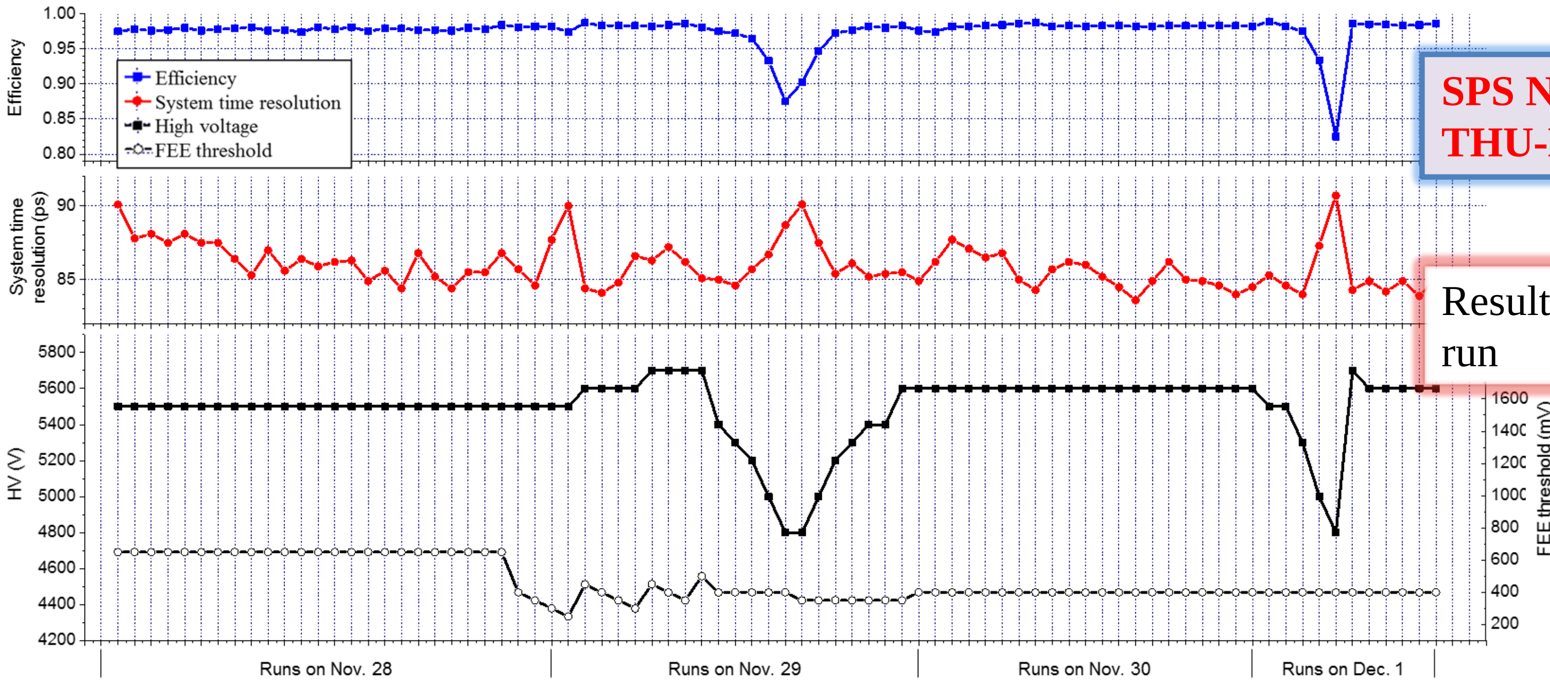
Up setting

Down setting



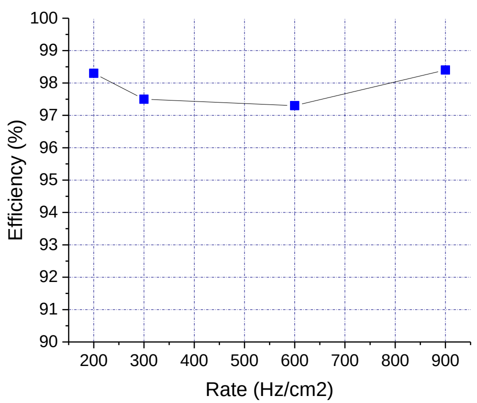
High rate test in February 2015 at SPS CERN
13 GeV Ar beam
Flux rate **around 1kHz/cm^2**

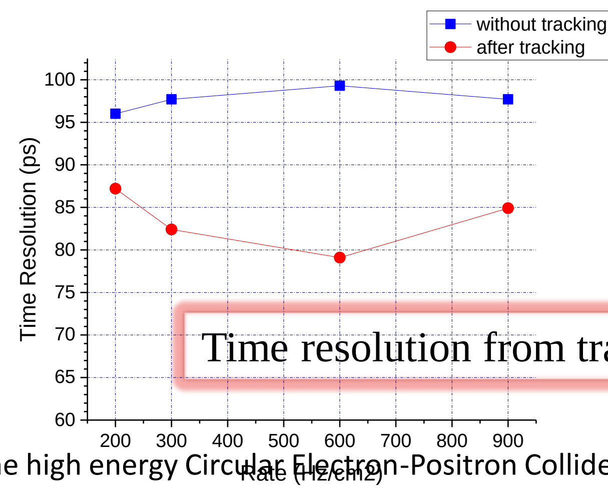
Performance of the prototype



SPS Nov 2015
THU-DU results

Results of each run

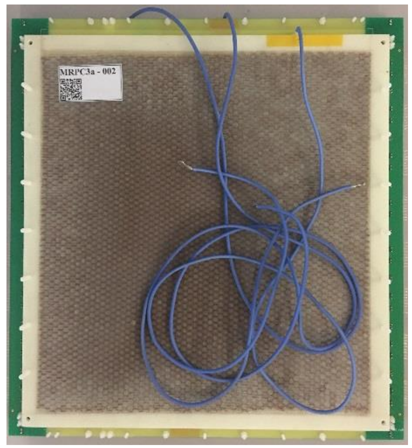


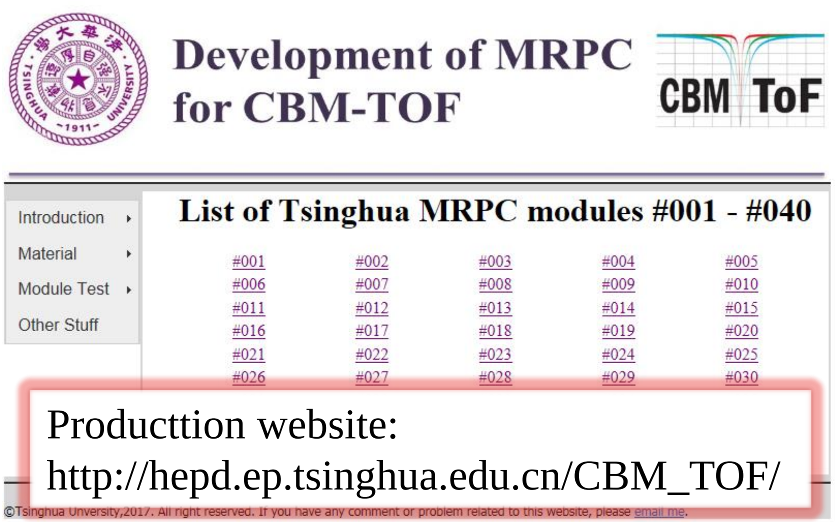


Time resolution from tracking method

Mass production of high rate MRPC

Two-dimensional code of MRPC



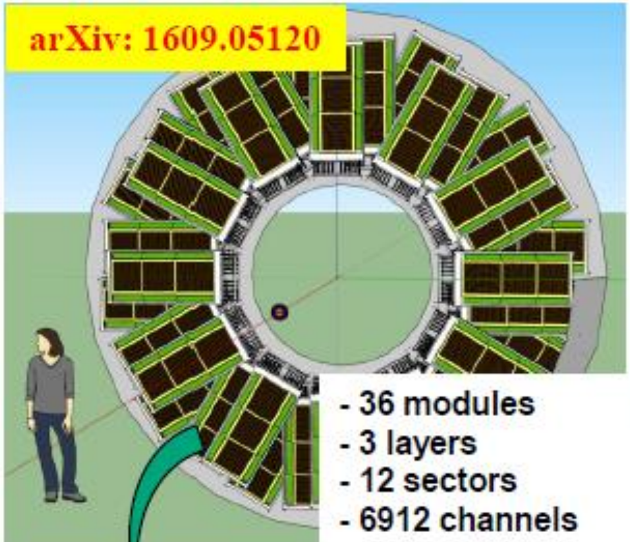


Producttion website:
http://hepd.ep.tsinghua.edu.cn/CBM_TOF/

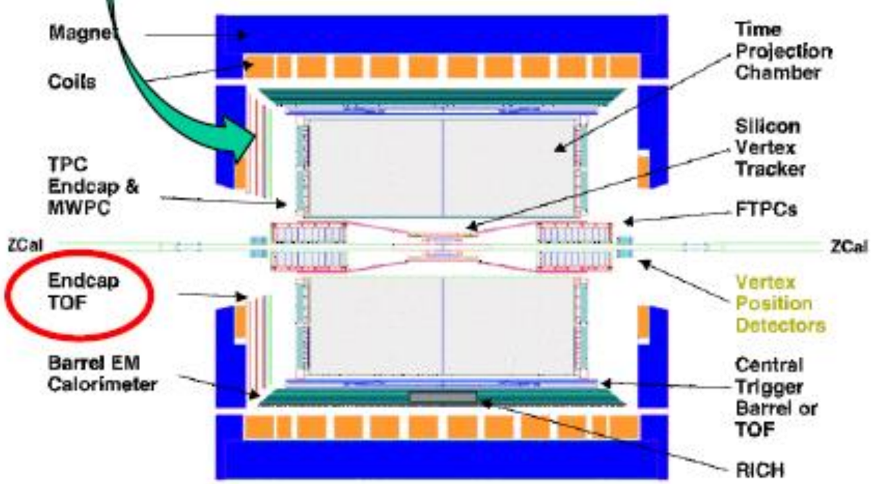
MRPC生产记录表 / MRPC3a Quality Assurance Table

MRPC ID	MRPC3a - 005							
玻璃 / Glass	来自箱号与批次 / Glass Batch No.			NO.9 151225	用料数量/Amount			6
	来自箱号与批次 / Glass Batch No.			NO.11 151225	用料数量/Amount			4
	来自箱号与批次 / Glass Batch No.				用料数量/Amount			
电极玻璃 / Electrode	面电阻 / Surface Resistance (MΩ/sq)			Point 1	Point 2	Point 3	Point 4	Point 5
	电极玻璃1 / Electrode 1			8	2	3	7	7
	电极玻璃2 / Electrode 2			3	3	4	3	3
	电极玻璃3 / Electrode 3			5	8	5	8	5
	电极玻璃4 / Electrode 4			8	4	3	5	5
蜂窝板 / Honeycomb	√							
PCB上下板 / Top & Bottom PCB	√							
PCB中间板 / Middle PCB	焊接保护电阻 / Protection Resistor		外侧64路信号与地之间电阻是否均为100kΩ / Resistance Measured on Outside Resistor			√	问题数量 / Unqualified	0
			内侧64路信号与地之间电阻是否均为200kΩ / Resistance Measured on Inside Resistor			√	问题数量 / Unqualified	0
	焊接双排插针 / Connector		16个插座与电路板的厚度是否均<6.7mm / Thickness of the connectors			√	问题数量 / Unqualified	0
Mylar膜 / Mylar	√							
PCB上下板高压 / Top & Bottom HV	√							
PCB中间板高压 / Middle HV	√							
鱼线 / Spacer	√							
厚度 / Thickness	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8
上下PCB / Between Top & Bottom PCB	11.44	11.47	11.44	11.41	11.57	11.45	11.59	11.52
上中PCB / Between Top & Middle PCB	4.61	4.77	4.67	4.76	4.66	4.79	4.72	4.77
下中PCB / / Between Bottom & Middle PCB	4.63	5.03	5.02	4.87	4.96	4.84	4.84	4.74
总厚度 / Total Thickness	25.98	25.92	26.11	26.12	26.03	26.13	26.15	26.05
组装人员签字 / Signature	杨泽林							
日期 / Date	08/09/2017							
备注 / Note								

CBM Phase0: eTOF @STAR



- 36 modules
- 3 layers
- 12 sectors
- 6912 channels

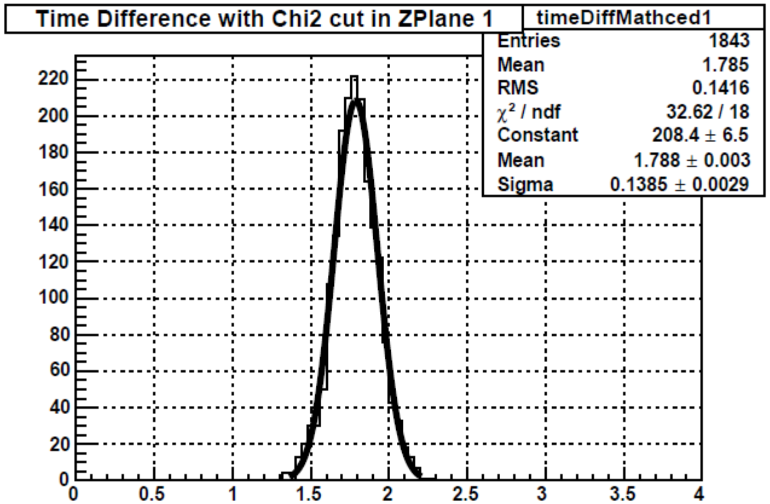


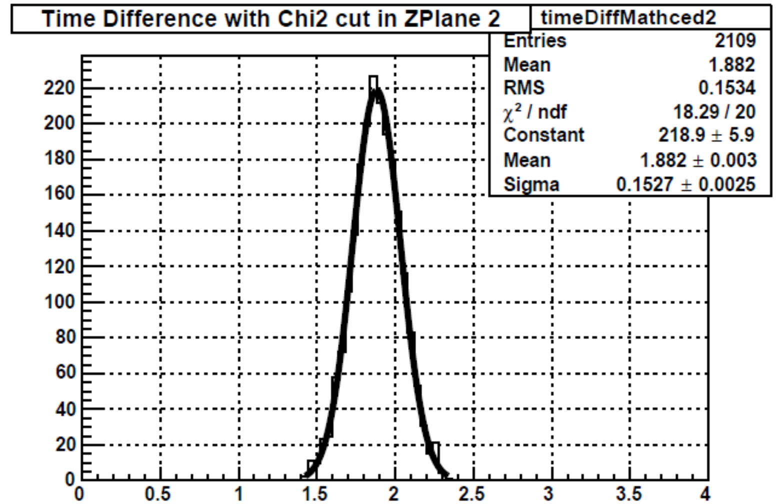
Time line

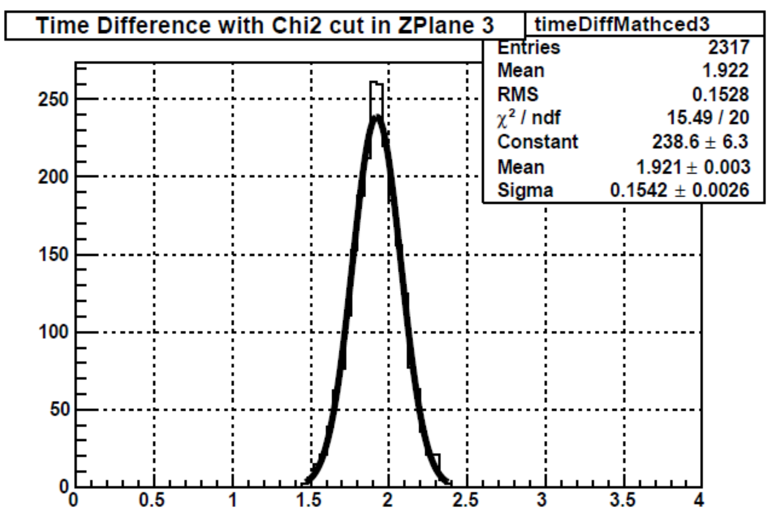
- Jan 2018 — shipping and installation of one sector
- Mar. 2018 — 2nd system integration test with one sector by participating in the Run18 beam time in STAR
- Fall 2018 — shipping all 33 modules including infrastructure (gas system, LV-, HV-power supply) to BNL
- Fall 2018 — Installation and commissioning
- Feb 2019/2020 — Start of the BES II campaign
- Summer 2021 — Decommissioning and shipping of all modules including infrastructure to FAIR

Time resolution

StETofAnalysisMaker – Time Resolution



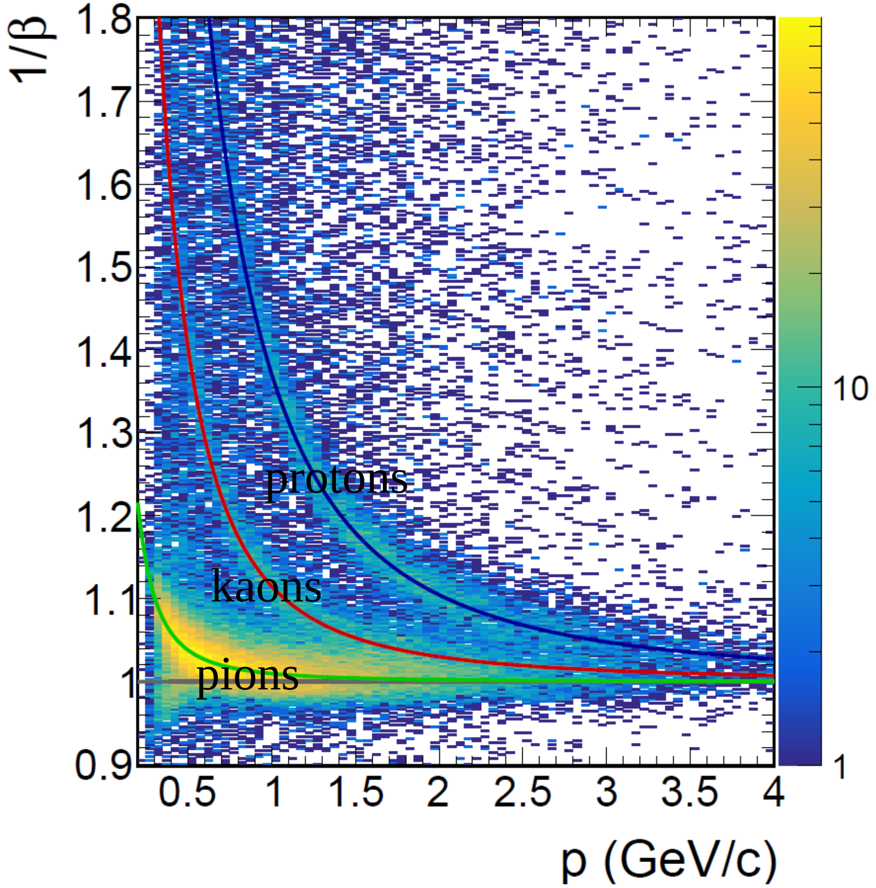


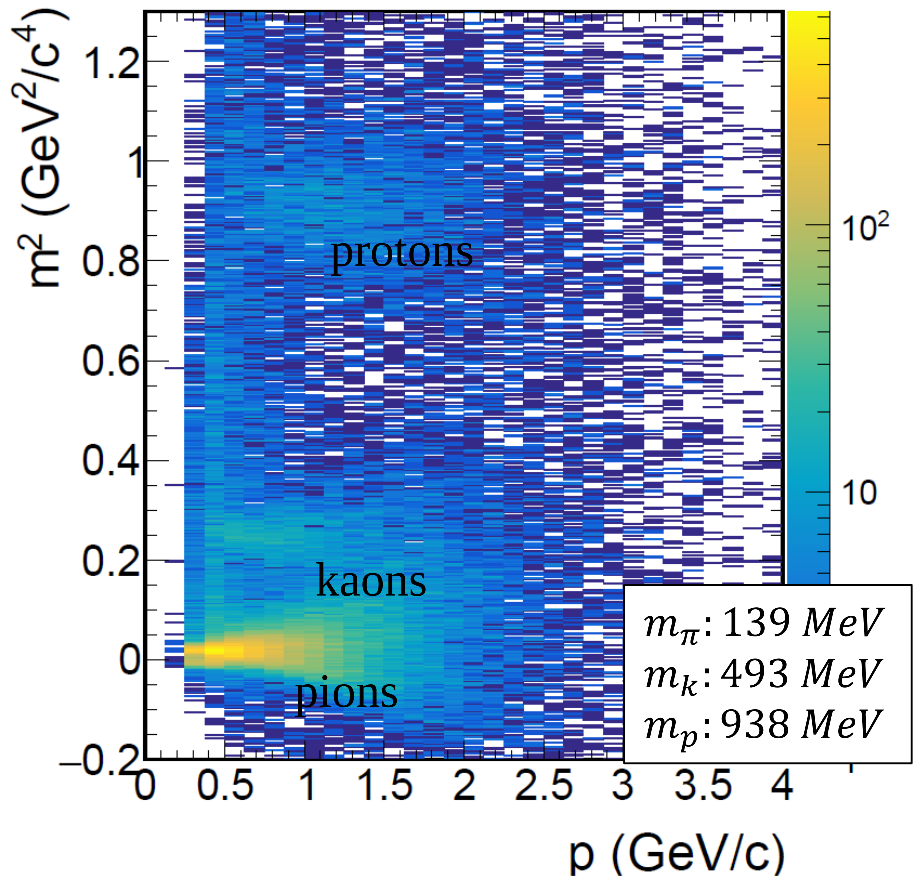


The independent resolution of each counter is around 100 ps (after divided by $\sqrt{2}$).
Should get improved with calibration.

StETofMatchMaker – PID Information

2018 Au Au 27GeV, 2M events





Overview of SoLID

Solenoidal Large Intensity Device

- Full exploitation of JLab 12 GeV Upgrade

  → A Large Acceptance Detector AND Can Handle High Luminosity (10^{37}-10^{39})

  Take advantage of latest development in detectors , data acquisitions and simulations

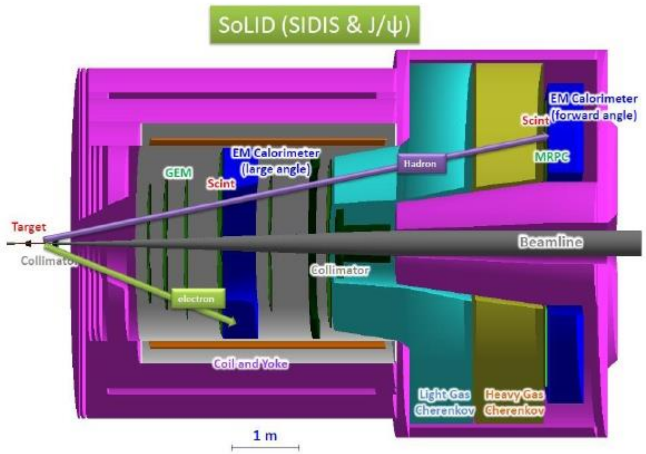
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-x region and threshold J/ψ

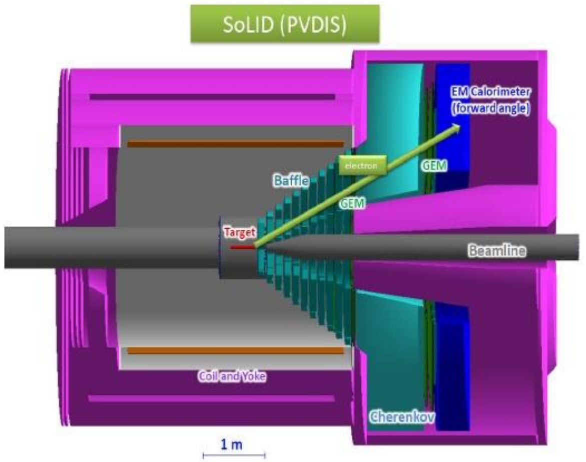
- 5 highly rated experiments approved (+3)

  Three SIDIS experiments, one PVDIS, one J/ψ production (+ three run group experiments)

- Strong collaboration (250+ collaborators from 70+ institutes, 13 countries)

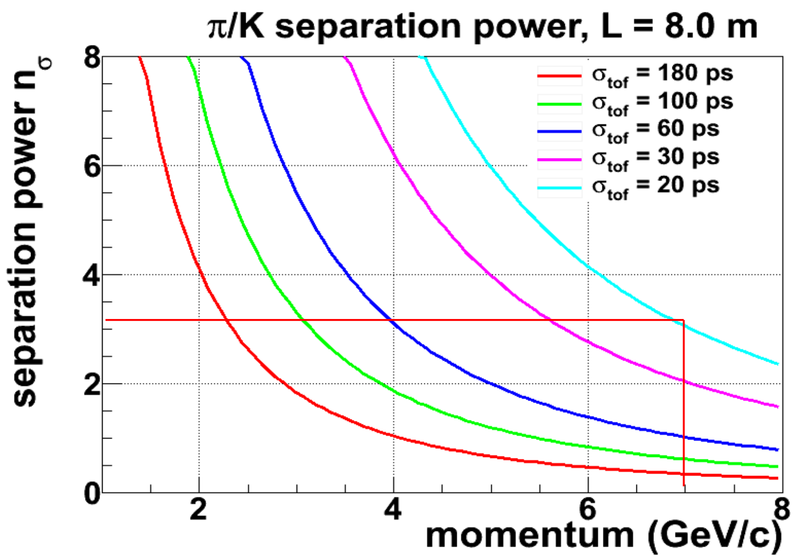
  Significant international contributions (Chinese collaboration)

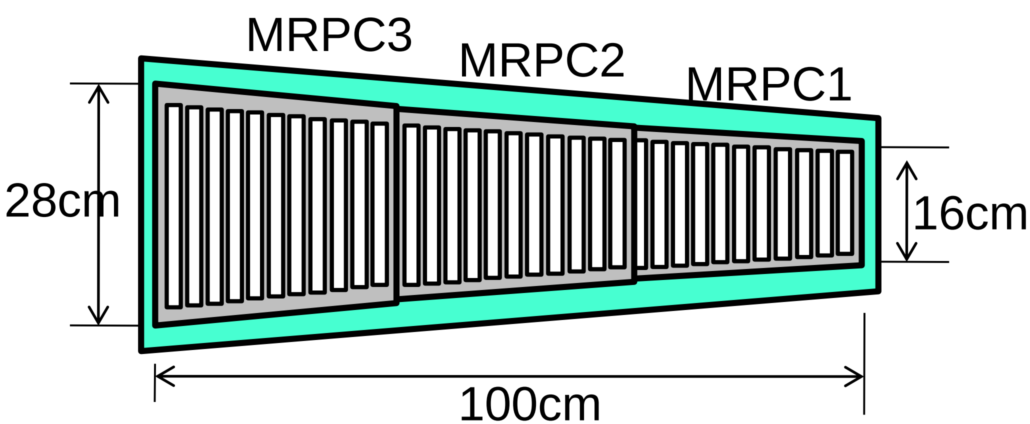




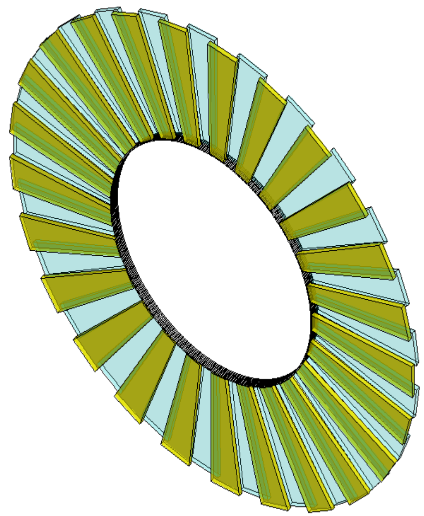
SoLID-TOF structure

- The MRPC is developed for the TOF of SoLID
- Main Requirements for TOF:
  - π/k separation up to 7GeV/c
  - Time resolution < 20ps
  - Rate capability > 20kHz/cm²





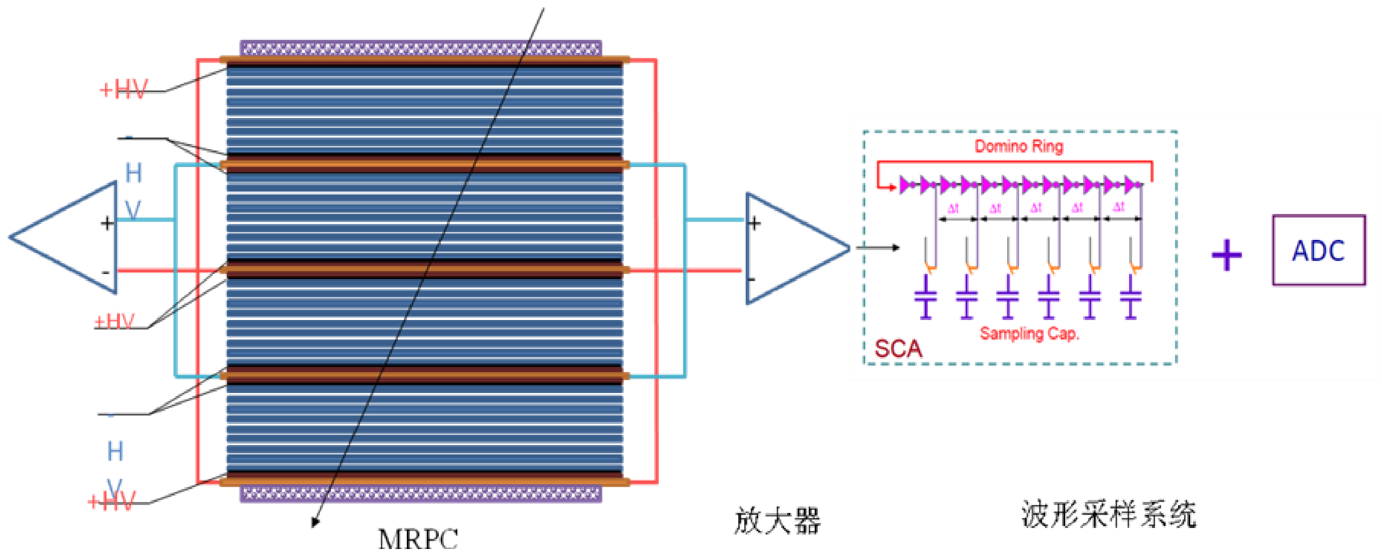
SoLID-TOF super module



SoLID-TOF structure

Technical route

- Challenge for both MRPC and electronics.
- Electronics: Fast amplifier + pulse sampling
- New analysis method: take the advantage of the entire waveform



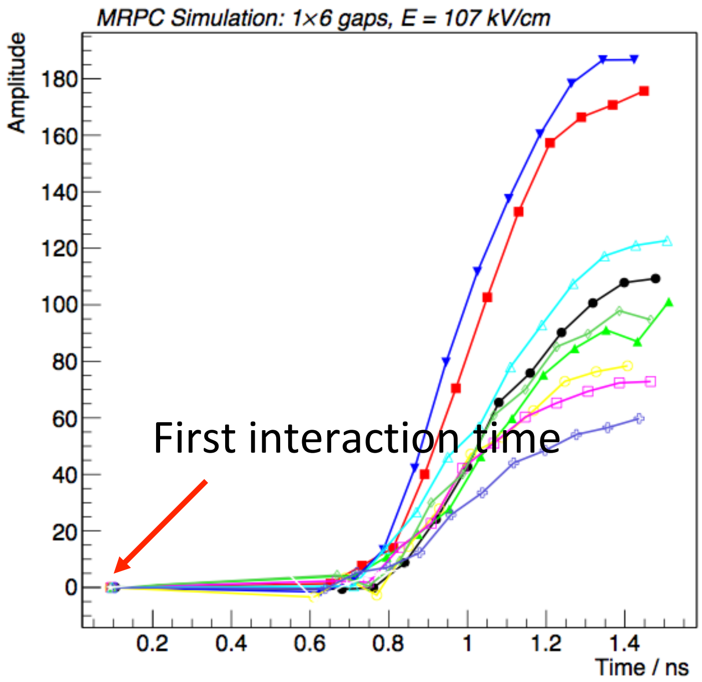
Neural network was used to reconstruct timing

- The analysis method is based on the neural network.
- Artificial neural network(NN): powerful && widely used in high energy physics
- Introduce NN to obtain good time resolution:
  —— Find out the patterns from the MRPC signal and estimate the particle 1st interaction time more precisely.

Learn from the simulation waveforms

1 Test with simulation data

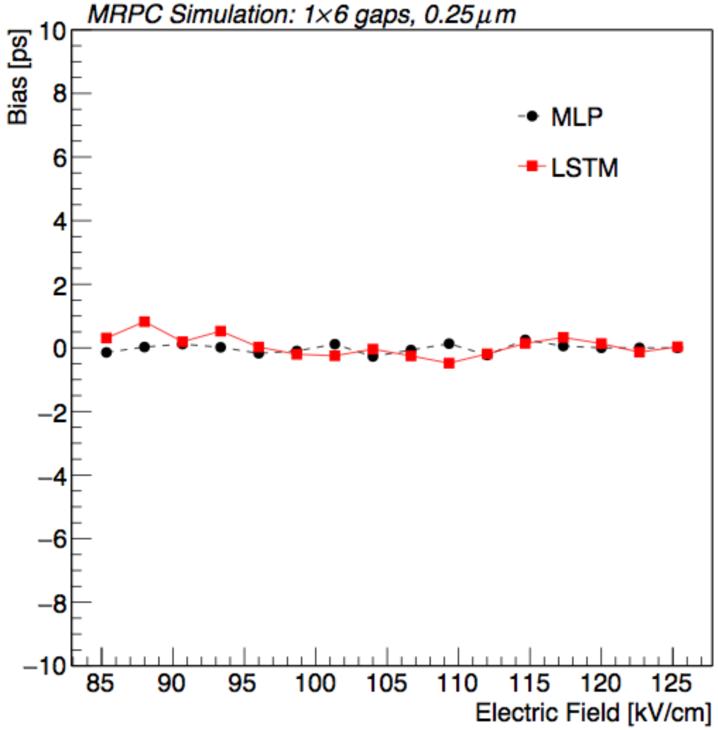
2 Test with experiment data



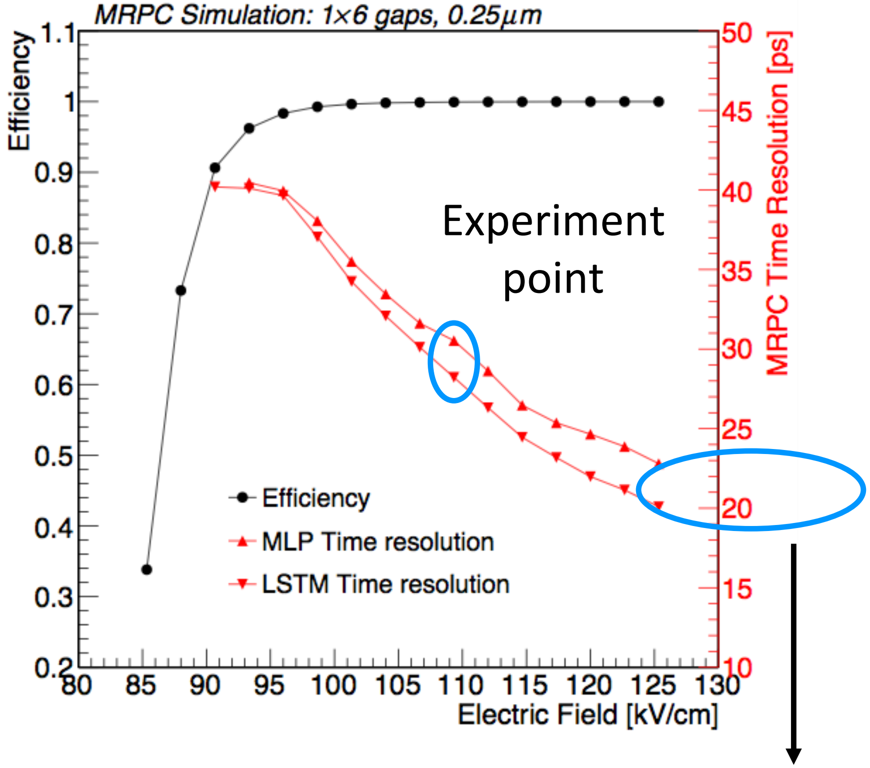
Simulation results

- Define bias: $t_{estimate} - t_{truth}$

Accuracy



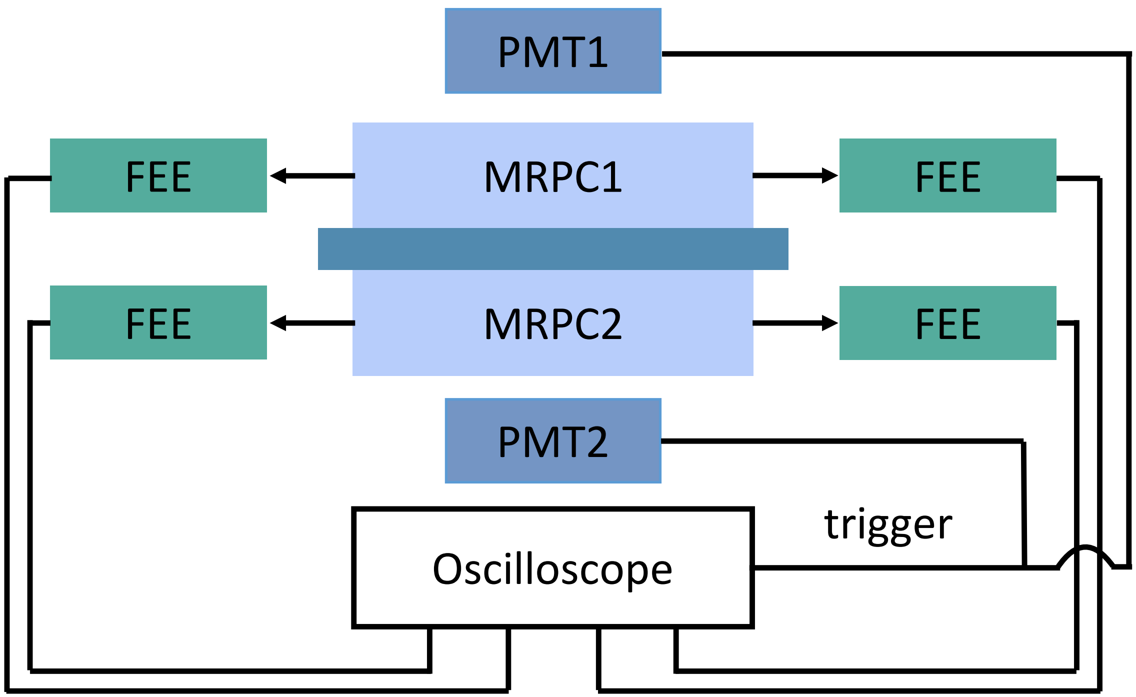
Precision

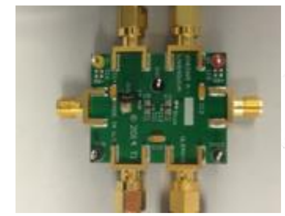


- Accuracy is good and stable
- The best time resolution can reach around 20 ps.

Experimental setup

- Experiment of the cosmic ray
- 2 identical MRPC: 6-gap, 0.25mm gap, working at E=109 kV/cm





- Oscilloscope bandwidth: 1 GHz
- Sampling rate: 10 GS/s

Leading edge: 700~800 ps

7~8 points along the edge

Experimental results

- The 4 waveforms are estimated by the LSTM models separately
- Define: $\Delta t = t_{MRPC1} - t_{MRPC2}$ for vertical particles

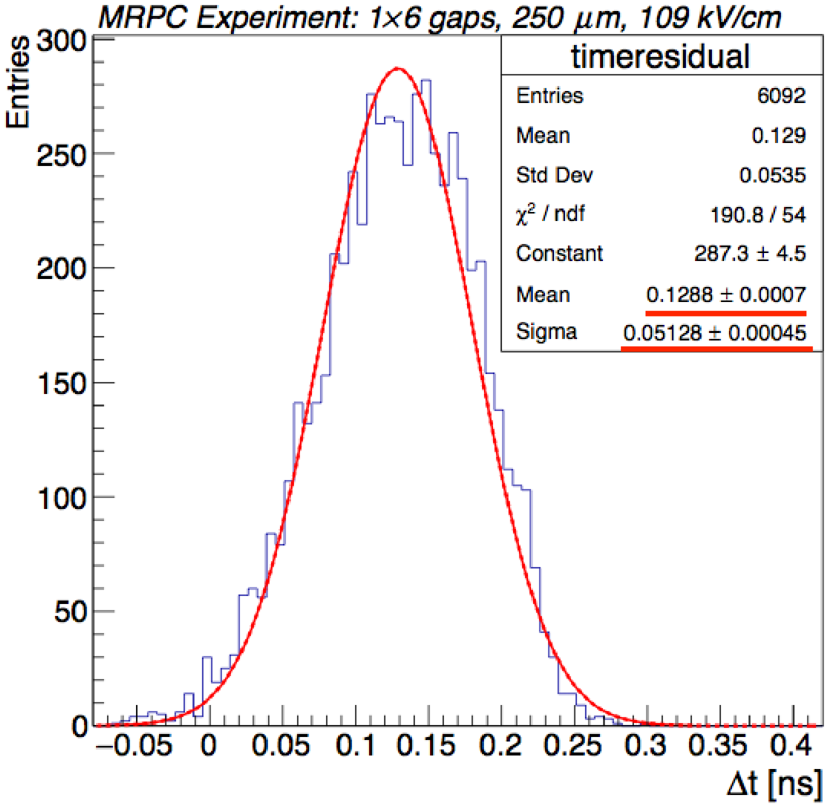
$$\Delta t_{true} = \frac{d_{MRPC} + d_{block}}{v} = \sim 130\ ps$$

- The time resolution of two MRPCs are independent:

$$\sigma_{MRPC} = \frac{\sigma(\Delta t)}{\sqrt{2}}$$

- With LSTM model, for vertical particles, the time resolution is:

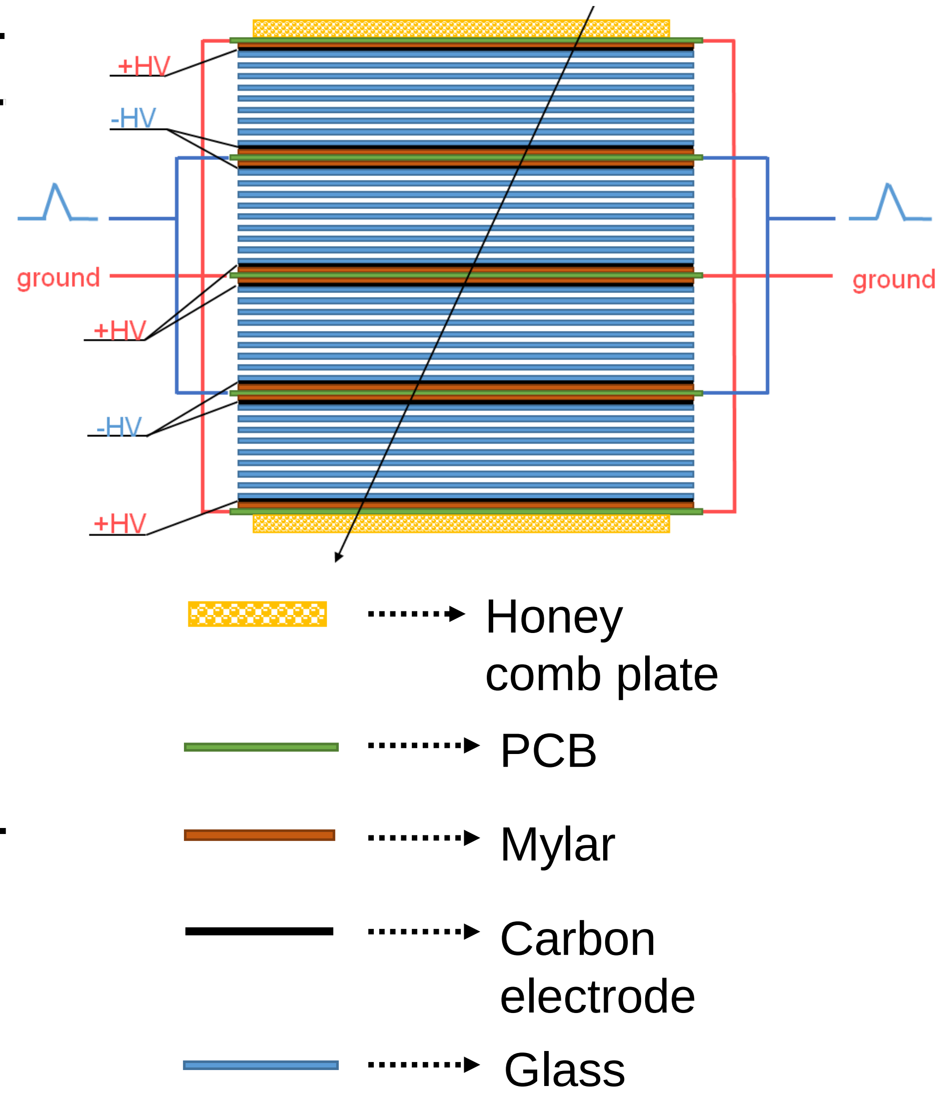
$$51.28/\sqrt{2} = 36.3\ ps$$



For MRPC of 6-gap, 0.25mm gas gap

Design of 3g MRPC for SoLID

Item	dimension/mm
Honeycomb	90×265×7.5
Outer PCB	120×298×0.6
Middle PCB1	120×298×1.2
Middle PCB2	120×328×1.2
Strip length	268
Strip width	7
Mylar	90×268×0.25
Glass	80×258×0.5
Carbon	72×250
Gas gap width	0.104
Number of gas gap	32



Analysis with neural network

- Test system: 2 MRPC

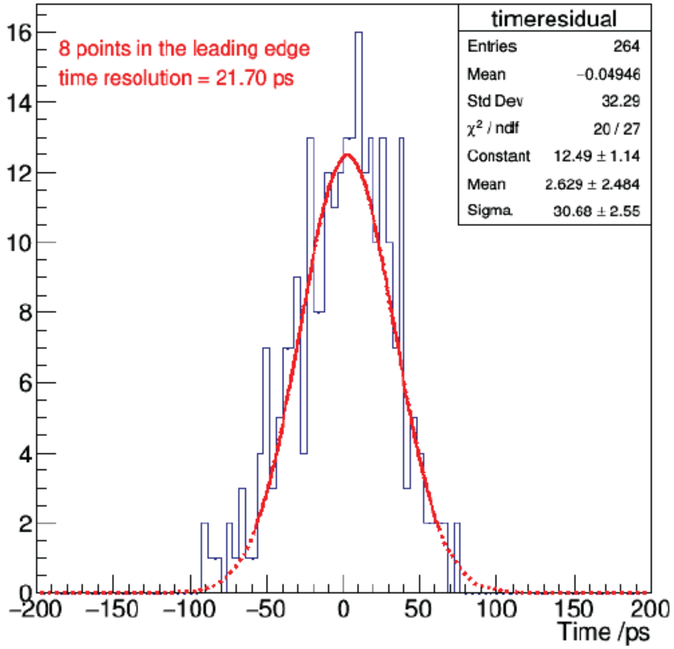
$$\sigma(\Delta t) = \sigma(t_{res1} - t_{res2}) = \sqrt{\sigma^2(t_{resi1}) + \sigma^2(t_{resi2})} = \sqrt{2\sigma^2_{MRPC}}$$
$$= \sigma(t_{true2} - t_{est2} - t_{true1} + t_{est1}) = \sigma(t_{est1} - t_{est2})$$
$$= \sigma(\frac{t_{est1l} + t_{est1r}}{2} - \frac{t_{est2l} + t_{est2r}}{2})$$

$$\sigma_{MRPC} = \frac{\sigma(\Delta t)}{\sqrt{2}}$$

- SCA+ADC waveform sampling
- Train with simulation data, test with experiment data
- Plot

$$Time = \frac{t_{est1l} + t_{est1r}}{2} - \frac{t_{est2l} + t_{est2r}}{2}$$

- The time resolution can reach 20 ps



Conclusions

- **MTRC-TOF played an important role in modern high energy nuclear physics experiments.**
- **High rate and high resolution TOF is being developed.**
- **New technology should be studied:**

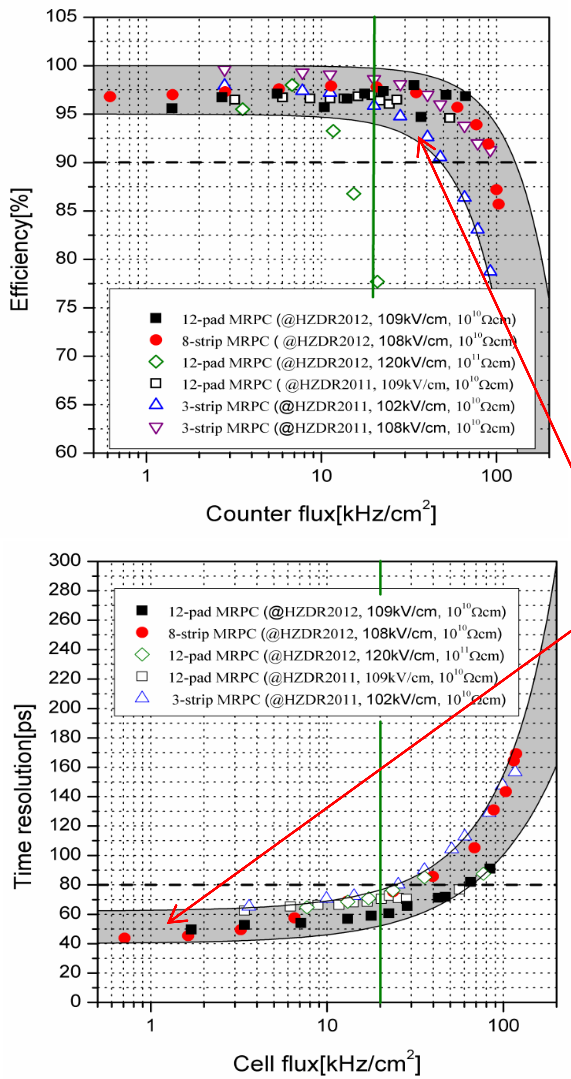
  New material (low resistive glass)

  New electronics (switched capacitor array (SCA) and high precision TDC)

  New analysis method (deep learning technology)

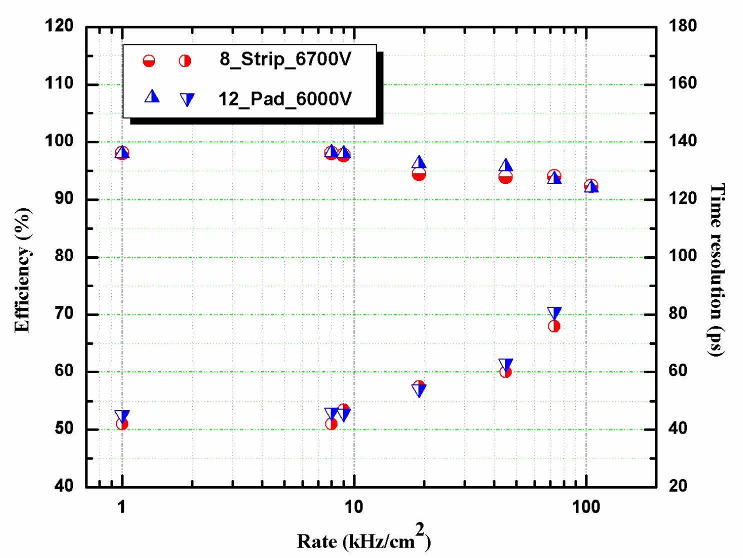
Thanks for your attention!

Rate capability of high rate MRPC



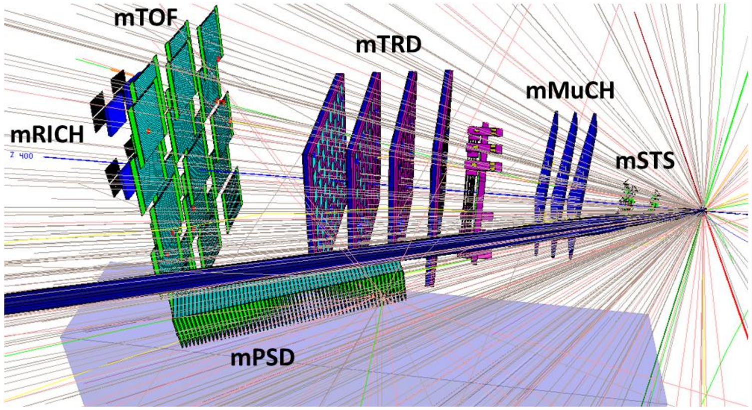
Rate: 70kHz/cm²
Time resolution: 40 ps

Test results at Nuclotron, Dubna，2013

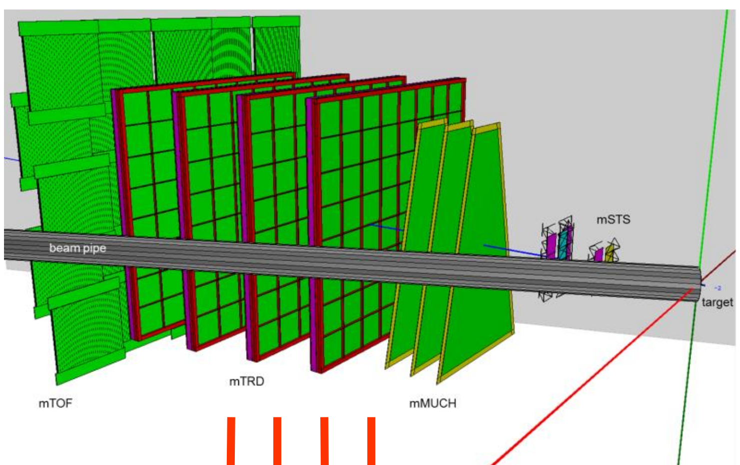


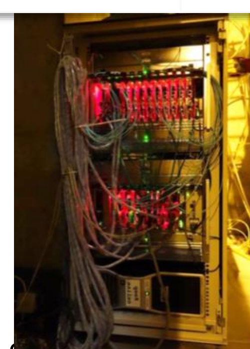
Even though the rate is 70kHz/cm², the efficiency is still higher than 90% and the time resolution is about 80ps.

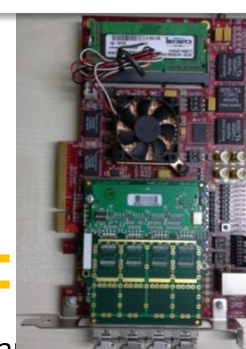
mCBM@SIS18



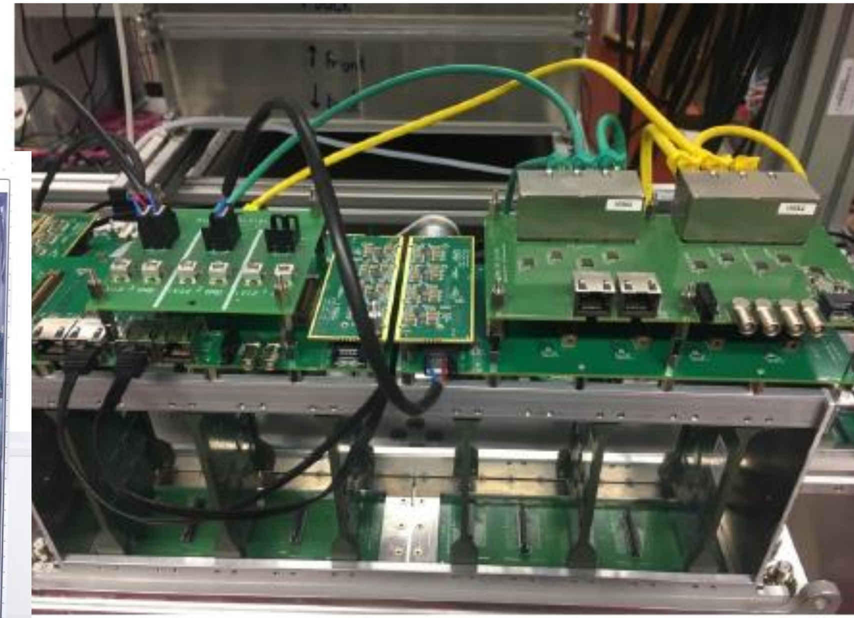
Schedule	
10/2017	HTD cave & beam line: preparation of construction, start of procurement
11/2017	HTD cave & beam line: start of construction
11/2017	mDAQ test stand @ Heidelberg operational
11/2017	installation of detector subsystems: **mechanical design freeze**
03/2018	HTD cave construction completed
04/2018	mFLES cluster @ Green IT Cube installed
05/2018	**installation of detector stations**
06/2018	start commissioning w/o beam
09/2018	**start commissioning with beam**

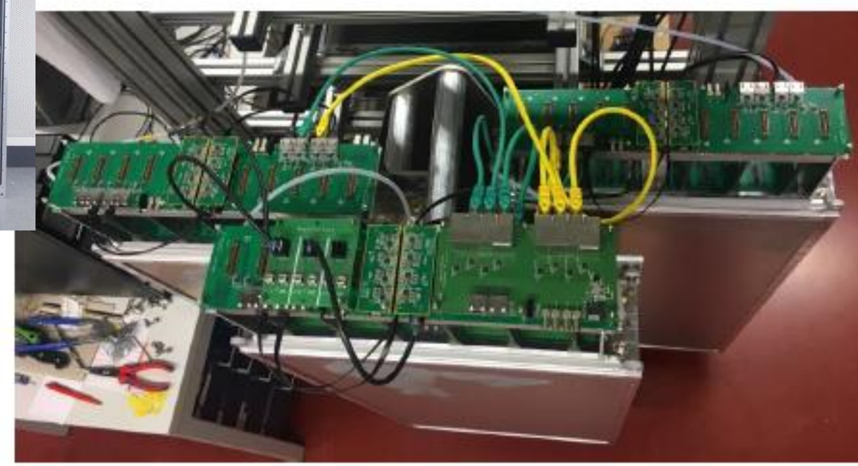




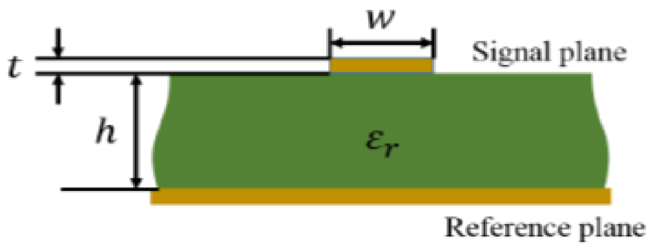


Production of modules for eTOF and mCBM

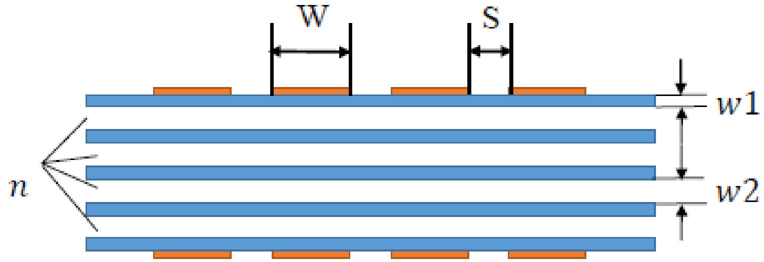




Approximate formula for impedance estimation



$$Z_0 = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln \frac{5.98h}{0.8w + t}$$



Coefficients: $a(1) - a(8)$
Number of gas gaps: n
Number of stacks: ns
Width of glass: w1
Width of gaps: w2
Width of strips: w
Equivalent dielectric constant: ε

Approximate formula for impedance estimation in MRPC detector:

$$Imp = \frac{\frac{a(1)}{\sqrt{\varepsilon + a(2)}} \times \log \frac{a(3) \times n \times w2 + a(4) \times (n+1) \times w1}{w - a(5)} + a(6) \times \sqrt{\frac{w}{n \times w2 + (n+1) \times w1}} + a(7) \times \log \frac{w1}{w2}}{ns + a(8)}$$

$$\varepsilon_{eq} = \left(\frac{n \times w2 \times \sqrt{\varepsilon_{air}} + (n+1) \times w1 \times \sqrt{\varepsilon_g}}{n \times w2 + (n+1) \times w1} \right)^2$$

Approximate formula for impedance estimation

Approximate formula for calculating the impedance of transmission lines in MRPC Detector:

$$Imp = \frac{\frac{a(1)}{\sqrt{\varepsilon + a(2)}} \times \log\frac{a(3) \times n \times w2 + a(4) \times (n+1) \times w1}{w - a(5)} + a(6) \times \sqrt{\frac{w}{n \times w2 + (n+1) \times w1}} + a(7) \times \log\frac{w1}{w2}}{ns + a(8)}$$

Coefficients: $a(1) - a(8)$

406.3467 ± 15.0495

8.6294 ± 1.0010

6.1138 ± 0.1998

0.6871 ± 0.0606

0.5577 ± 0.0289

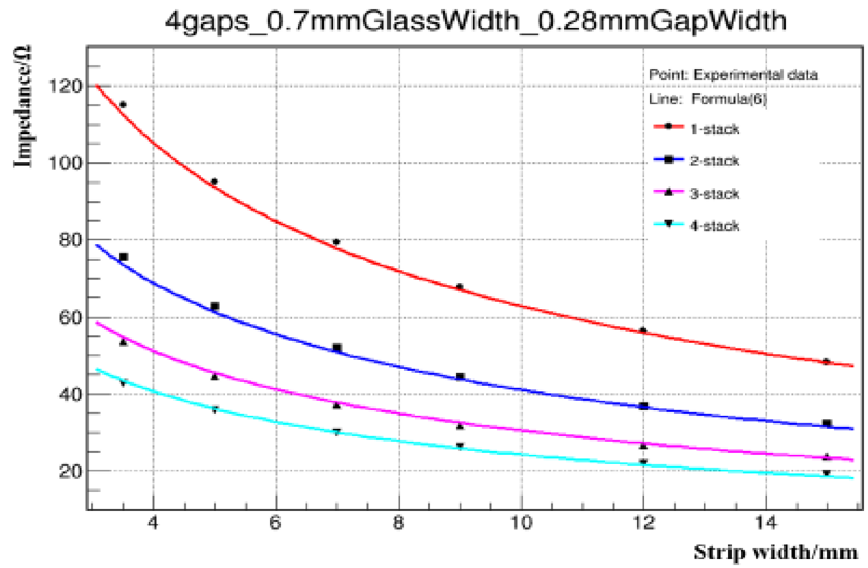
59.0823 ± 1.8964

37.5319 ± 1.8673

0.895 ± 0.0089

RMSE= 1.2043

R-square= 0.9977



17

Waveform simulation

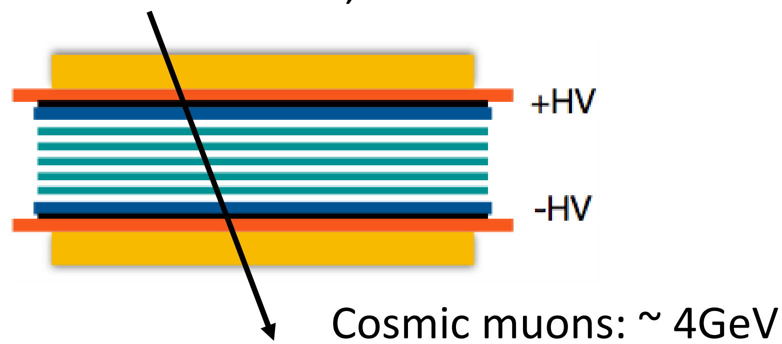
Design the structure
↓
Shoot a particle
↓
Primary interactions
↓
Drifting & Avalanche
↓
Original current signal
↓
Electronics

- MRPC structure

  6-gas MRPC

  Gap/glass thickness: 0.25/0.7 mm

  Gas: 90% $C_2H_2F_4$, 5% C_4H_{10} and 5% SF_6



- Avalanche through drifting

$$\frac{d\bar{n}}{dx} = (\alpha - \eta)\bar{n}$$

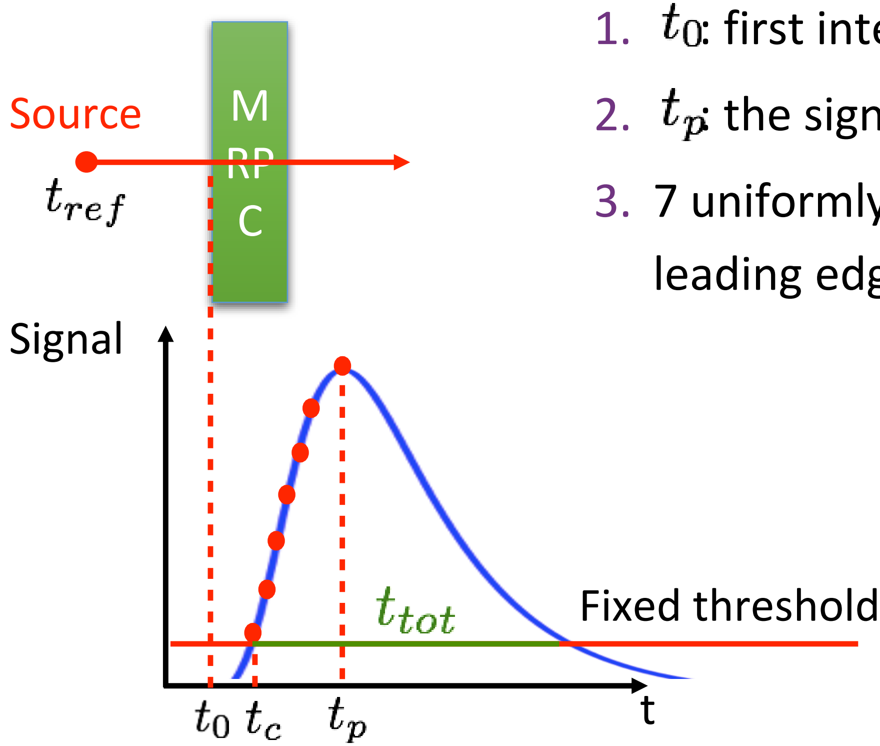
α : Townsend coefficient
η : Attachment coefficient

- Induced current: $i(t) = \frac{E_W \cdot v}{V_W} e_0 N(t)$

- Front-end electronics + noise

*F. Wang, et al., A standalone simulation framework of the mrpc detector read out in waveforms, arXiv:1805.02387.

Simulation data



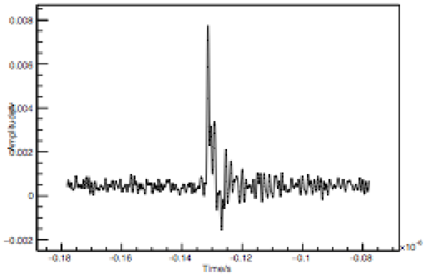
Simulation dataset :

1. t_0: first interaction happens
2. t_p: the signal reach the peak
3. 7 uniformly distributed points along the leading edge

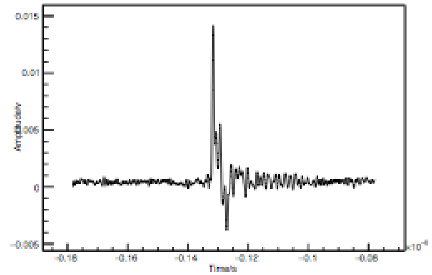
Signal waveform

- Compare the waveform

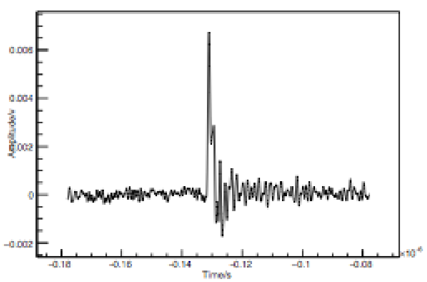
1L



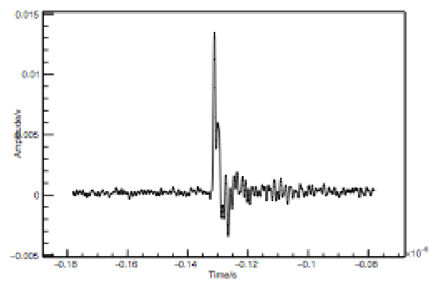
1R



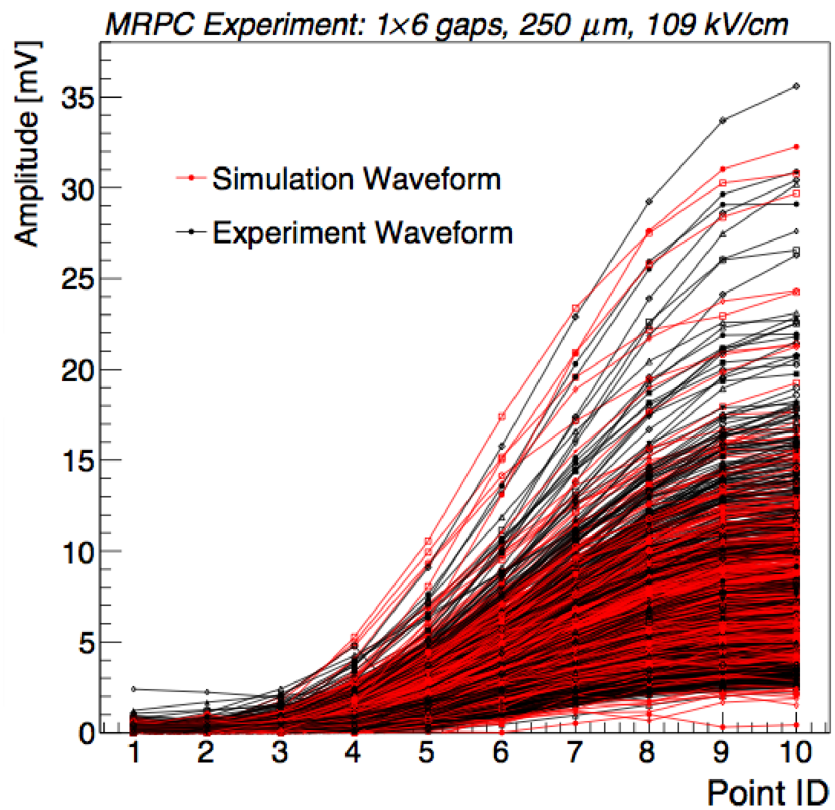
2L



2R



Waveforms of 1 event



Nearly the same!

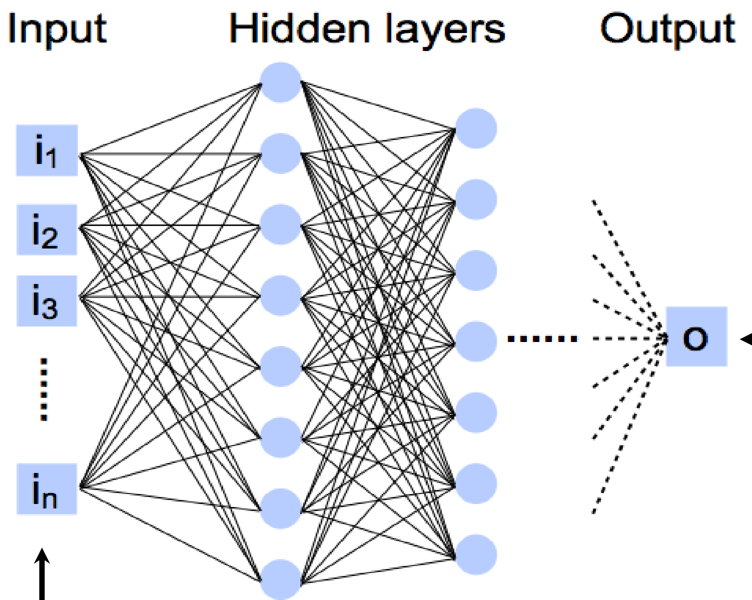
Still with differences!

One NN： Multilayer perception (MLP)

- Multilayer perceptron (MLP)

$$\underline{F_i(\vec{x})} = h(\sum_j(\omega_{ij}^2 g(\ldots g(\sum_k(\omega_{jk}^1 g(\sum_l(\omega_{kl}^0 \underline{x_l} + \chi_k^0)\ldots + \chi_j^1) + \chi_i^2)$$

Output　　　　Input



- Activation function: g and h —— tanh
- Weights: $\omega^{0,1\ldots}$, $\chi^{0,1\ldots}$
- "Dropout": avoid overfitting

The length of the leading edge t_l

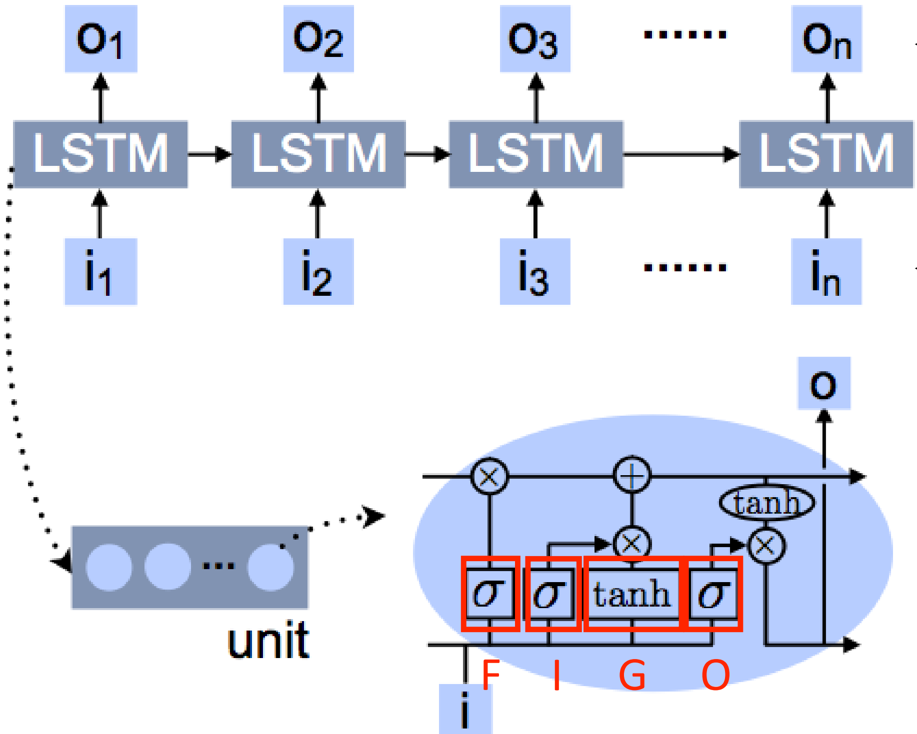
Time of the very first interaction: $t_0 = t_p - t_l$

Several uniformly distributed points along the leading edge

- Train/validate/test set: 20/10/10 k
- Tensorflow & GPU: GTX 1080 Ti
- ~ 10 mins for training

Another NN: LSTM

- Recurrent neural networks(RNN): Long Short Term Memory network(LSTM)



The length of the leading edge t_l

Several uniformly distributed points along the leading edge

f : forget gate: Whether to erase

I : Input gate, whether to write

g: gate gate, How much to write

o: output gate, How much to reveal

- Train/validate/test set: 20/10/10 k
- Tensorflow & GPU: GTX 1080 Ti

> 30 mins for training