Status of MRPC TOF technology

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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

Standard parameters:
- Resistivity of glass: $\sim 10^{12} \Omega \cdot \text{cm}$
- Working gas: 90% Freon + 5% iso-butane + 5% SF6
- Time resolution <100 ps
- Efficiency >95%
- Charge: a few PC
- Dark current: a few nA
- Noise $\sim 1 \text{Hz/cm}^2$
- 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)

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How to increase rate of MRPC

The voltage drop in the gas gap:

\[ \overline{V}_{\text{drop}} = V_{ap} - \overline{V}_{\text{gap}} = \overline{IR} = \overline{q}\phi\rho d \]

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

SoLID (SIDIS He3)

JLab-SoLID TOF
High rate and 20ps resolution

FAIR-CBM TOF
High rate - low resistive glass

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Key technology

1\textsuperscript{st} generation TOF:
- Requirement: Time resolution: <80ps
  Rate : <1kHz/cm^2
- Technology: common glass MRPC+NINOs +HPTDC
- Analysis method: TOT slewing correction

2\textsuperscript{nd} generation TOF:
- Requirement: Time resolution: <80ps
  Rate : 30kHz/cm^2
- Technology: low resistive glass MRPC+PADI +GET4
- Analysis method: TOT slewing correction

3\textsuperscript{rd} generation TOF:
- Requirement: Time resolution: <20ps
  Rate : 20kHz/cm^2
- Technology: low resistive glass MRPC+SCA +ADC
- Analysis method: TOT slewing correction
  Deep learning+ Neural network
RHIC-STAR

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

Particle identification with TPC+TOF
pion/kaon: pT ~ 1.6 GeV/c; proton pT ~ 3.0 GeV/c
Strange hadrons (K^0, Λ, Ξ, Ω) reconstructed by the decay topology
STAR-TOF MRPC

PC board 1.5mm
mylar 0.35mm

Long side view
Glass: $\sim 4 \times 10^{12} \Omega \cdot \text{cm}$
Carbon tape: 500k $\Omega / \square$
Gas gap: $6 \times 0.22 \text{mm}$
Working gas: 95% F134a+5% iso-butane
Time resolution: 70ps
Efficiency >90%
Rates capability: <500Hz/cm²
MRPC mass production
TOF PID:
\[ \pi/k \sim 1.6 \text{ GeV/c}, \]
\[ (\pi,k)/p \sim 3.0 \text{ GeV/c} \]
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 $\sigma_T \sim 80$ ps
- Efficiency $> 95\%$
- Rate capability $\leq 30$ kHz/cm$^2$
- Polar angular range $2.5^\circ - 25^\circ$
- Occupancy $< 5\%$
- Low power electronics ($\sim$100.000 channels)
- Free streaming data acquisition

Au+Au, Center, 10AGeV
Simulated with CBM ROOT
Development of low resistive glass

Performance of the glass

<table>
<thead>
<tr>
<th>Performance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal dimension</td>
<td>32cm × 30cm</td>
</tr>
<tr>
<td>Bulk resistivity</td>
<td>$10^{10}$ Ω cm</td>
</tr>
<tr>
<td>Standard thickness</td>
<td>0.7, 1.1mm</td>
</tr>
<tr>
<td>Thickness uniformity</td>
<td>20 µm</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>&lt; 10nm</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>7.5 - 9.5</td>
</tr>
<tr>
<td>DC measurement</td>
<td>Ohmic behavior stable up to 1 C/cm²</td>
</tr>
</tbody>
</table>

Glass mass production
Yield >100m²/month

Online test system. The efficiency and time resolution can be obtained by cosmic ray while irradiated by X-rays. 0.1C/cm² charge is accumulated in 35 days.
Rate capability of high rate MRPC

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

Test results at Nuclotron, Dubna, 2013

Rate: 70kHz/cm²
Time resolution: 40 ps
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
High rate test in February 2015 at SPS CERN
13 GeV Ar beam
Flux rate around 1kHz/cm²
Performance of the prototype

Results of each run

Time resolution from tracking method

SPS Nov 2015 THU-DU results

Efficiency

System time resolution

HV (V)

High voltage

FEE threshold

Rate (Hz/cm²)

Time Resolution (ps)

without tracking

after tracking

Efficiency (%)

Rate (Hz/cm²)

Performance of the prototype
### Mass production of high rate MRPC

#### Development of MRPC for CBM-TOF

<table>
<thead>
<tr>
<th>List of Tsinghua MRPC modules #001 - #040</th>
</tr>
</thead>
<tbody>
<tr>
<td>#001</td>
</tr>
<tr>
<td>#006</td>
</tr>
<tr>
<td>#011</td>
</tr>
<tr>
<td>#016</td>
</tr>
<tr>
<td>#021</td>
</tr>
<tr>
<td>#026</td>
</tr>
</tbody>
</table>

#### Production website:
http://hepd.ep.tsinghua.edu.cn/CBM_TOF/

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**MRPC生产记录表 / MRPC3a Quality Assurance Table**

<table>
<thead>
<tr>
<th>MRPC ID</th>
<th>MRPC ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO.23</td>
<td>151219</td>
</tr>
<tr>
<td>NO.2</td>
<td>151223</td>
</tr>
<tr>
<td>Point 1</td>
<td>Point 2</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Point 3</td>
<td>Point 4</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Point 5</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

**PCB上端 / Top & Bottom PCB**

| No.11   | 151225  |
| Point 1 | Point 2 |
| 8       | 2       |
| Point 3 | Point 4 |
| 3       | 7       |
| Point 5 |
| 7       |

**PCB下端 / Middle PCB**

| No.10   | 151225  |
| Point 1 | Point 2 |
| 5       | 4       |
| Point 3 | Point 4 |
| 5       | 5       |
| Point 5 |
| 5       |

**内侧 / Inside Resistor**

| 内侧64路信号与地之间电阻是否均为200kΩ /
| Resistance Measured on Inside Resistor |
| 内侧64路信号与地之间电阻是否均为200kΩ /
| Resistance Measured on Inside Resistor |
| 内侧64路信号与地之间电阻是否均为200kΩ /
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| Resistance Measured on Inside Resistor |
| 内侧64路信号与地之间电阻是否均为200kΩ /
| Resistance Measured on Inside Resistor |
| 内侧64路信号与地之间电阻是否均为200kΩ /
| Resistance Measured on Inside Resistor |

**外侧 / Outside Resistor**

| 外侧64路信号与地之间电阻是否均为200kΩ /
| Resistance Measured on Outside Resistor |
| 外侧64路信号与地之间电阻是否均为200kΩ /
| Resistance Measured on Outside Resistor |
| 外侧64路信号与地之间电阻是否均为200kΩ /
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| 外侧64路信号与地之间电阻是否均为200kΩ /
| Resistance Measured on Outside Resistor |
| 外侧64路信号与地之间电阻是否均为200kΩ /
| Resistance Measured on Outside Resistor |

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**Note**

- [RPC2018, Puerto Vallarta Mexico, 19-23 Feb, 2018](#)
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 \(J/\psi\)
• 5 highly rated experiments approved (+3)
  Three SIDIS experiments, one PVDIS, one \(J/\psi\) production (+ three run group experiments)
• Strong collaboration (250+ collaborators from 70+ institutes, 13 countries)
  Significant international contributions (Chinese collaboration)
The MRPC is developed for the TOF of SoLID

Main Requirements for TOF:
- $\pi/k$ separation up to 7GeV/$c$
- Time resolution < 20ps
- Rate capability > 20kHz/cm$^2$

SoLID-TOF structure

\[ \frac{\pi}{K} \text{ separation power, } L = 8.0 \text{ m} \]

SoLID-TOF super module

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RPC2018, Puerto Vallarta Mexico, 19-23 Feb, 2018
### Design of 3\textsuperscript{g} MRPC for SoLID

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

![Diagram of 3\textsuperscript{g} MRPC for SoLID](image)

- Honeycomb plate
- PCB
- Mylar
- Carbon electrode
- Glass

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Readout chain

- MRPC
- Fast amplifier
- Pulse sampling
- Gas box
- Waveform Digitizer DT5742
  - DRS4-V5 chip
  - 16 channels
  - 12bit 5GS/s
  - ~ 8 points for leading edge of MRPC
<table>
<thead>
<tr>
<th>Chip</th>
<th>Sampling Frequency (GHz)</th>
<th>Bandwidth GHz</th>
<th>Number of samples</th>
<th>Number of channels</th>
<th>Readout frequency (MHz)</th>
<th>Resolution (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSEC4</td>
<td>4 to 15</td>
<td>1.5</td>
<td>256</td>
<td>6</td>
<td>40 to 60</td>
<td>9</td>
</tr>
<tr>
<td>SAMPIC</td>
<td>3 to 8.2</td>
<td>1.6</td>
<td>64</td>
<td>16 – 8 (at 10 GHz)</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>DRS4</td>
<td>0.7 to 5 GHZ</td>
<td>0.950</td>
<td>1024</td>
<td>9</td>
<td>33</td>
<td>1</td>
</tr>
<tr>
<td>DRS5</td>
<td>10</td>
<td>3</td>
<td>4096</td>
<td>32</td>
<td>300</td>
<td>5</td>
</tr>
<tr>
<td>PSEC5</td>
<td>5 to 15</td>
<td>1.5 to 2</td>
<td>32768</td>
<td>4</td>
<td>500</td>
<td>5</td>
</tr>
</tbody>
</table>
Artificial neural networks (NN) are powerful tools for solving complex pattern recognition problems characterized by significant non-linearity.

Widely used in high energy physics.

For example, several sets of NN are used in the tracking reconstruction in ATLAS experiment.

Introduce NN to MRPC?

Training the NN with simulation data, and test with experiment data.
Comparison

**Threshold method**

From leading edge $\rightarrow$ Particle incident time

- Avalanche progress
- Charge induce
- Shaped by electronics

**Neural network**

Signal

Number of samples on slope

$\Delta t = \frac{\Delta u}{U} \cdot t_r = \frac{\Delta u}{U \sqrt{n}} \cdot t_r = \frac{\Delta u}{U} \frac{t_r}{ \sqrt{t_r \cdot f_s}} = \frac{\Delta u}{U} \frac{\sqrt{t_r}}{ \sqrt{f_s}}$

$\frac{1}{SNR}$
Neural network analysis method

- Determine structure of MRPC
- Construct NN
- Detector simulation -> Pulse shape
- Training NN
- Input measured pulse -> Timing
MRPC simulation

- Physics model—primary ionization:
- Photo Absorption Ionization (PAI) model
- Induced charge signal
- Shaped by electronics
- Train neural network

See Fuyue’s poster:
A neural network based algorithm for MRPC time reconstruction
Analysis with neural network

- Feed the waveform into a fully connected neural network
- 5 hidden layers
- 8 points along the leading edge
- Peaktime as a time reference
- TMVA package

Waveform

Particle arrived time

Signal

Peaktime

Variable 1:
Variable 2:
Variable 3:
Variable 4:
Variable 5:
Variable 6:
Variable 7:
Variable 8:
Variable 22:
Bias node:
Test the model with the experiment data and get the estimated time.

For 1L, 1R, 2L, 2R, we will get:

\[
t_{est1} = \frac{t_{estimated1L} + t_{estimated1R}}{2}
\]

\[
t_{est2} = \frac{t_{estimated2L} + t_{estimated2R}}{2}
\]
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

✓ Time of flight system (TOF) based on MRPC technology is widely used and played an important role in modern high energy nuclear physics experiments.

✓ With the increase of accelerator energy and luminosity, many experiments have increasingly demand on the TOF for particle identification to have high resolution TOF under high data rate environment.

✓ New technology such as New material (low resistive glass), New electronics (switched capacitor array (SCA) and precision TDC ) will be used in TOF system. New analysis method such as deep learning technology will play an very important role!
Thanks for your attention!