High rate and time resolution
TOF for SoLID

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Outline:
• Introduction MRPC-TOF and SoLID
• Development of high rate and high precision MRPC
• Next to do
• Conclusions
Introduction of MRPC

Standard parameters:
- Resistivity of glass: $\sim 10^{12} \Omega \cdot \text{cm}$
- Time resolution $< 100 \text{ps}$
- Efficiency $> 95$
- Dark current: a few nA
- Noise $< 1 \text{Hz/cm}^2$

- MRPC is made of thin glass, large area and cheap
- The inner glasses are floating, take and keep correct voltage by electrostatics. It is transparent to fast signals
- Thin gap $\rightarrow$ good timing
- Multi-gap $\rightarrow$ high efficiency

1. Application in nuclear physics experiments
2. Application in industry (Muon tomography)
3. Application in medicine (TOF-PET)
With the increase of accelerator energy and luminosity, the requirement is also rigorous.

Three generation MRPC-TOF

1\textsuperscript{st} MRPC-TOF
STAR-TOF, time: 80ps

2\textsuperscript{nd} MRPC-TOF
CBM-TOF, rate: 20kHz/cm\textsuperscript{2}, time: 80ps

3\textsuperscript{rd} MRPC-TOF
SoLID-TOF, rate: 20kHz/cm\textsuperscript{2}, time: 20ps
Motivation of 12 GEV Upgrade

• JLab 6 GeV: precision measurements
  high luminosity \(10^{39}\) but small acceptance (HRS/HMS: < 10 msr)
or large acceptance but low luminosity (CLAS6: \(10^{34}\))

• JLab 12 GeV upgrade opens up a window of opportunities (DIS, SIDIS, Deep Exclusive Processes) to study valence quark (3-d) structure of the nucleon and other high impact physics (PVDIS, J/\(\psi\), …)

• High precision in multi-dimension or rare processes requires very high statistics \(\rightarrow\) large acceptance and high luminosity

• CLAS12: luminosity upgrade (one order of magnitude) to \(10^{35}\)

• To fully exploit the potential of 12 GeV, taking advantage of the latest technical (detectors, DAQ, simulations, …) development

\(\rightarrow\) SoLID: large acceptance detector can handle \(10^{37}\) luminosity (no baffles) \(10^{39}\) with baffles
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)
Particle rate entering MRPC

- Dominant by photon in MeV
- $\gamma: 250\text{kHz/cm}^2$
- $e: 5\text{kHz/cm}^2$
- $n: 3\text{kHz/cm}^2$
Energy of Photon, electron and neutron

- Energy range
  - $\gamma$: $10^{-5} - 10\text{GeV}$
  - $e$: $10^{-6} - 10\text{GeV}$
  - $n$: $10^{-6} - 1\text{GeV}$
Particle rate detected by MRPC

- Detected particle rate
  - $\gamma$: 12.5kHz/cm²
  - e: 5kHz/cm²
  - n: 0.05kHz/cm²

Total: 18kHz/cm²
Main requirements for TOF

- The MRPC is developed for the TOF of SoLID
- Main Requirements for TOF:
  - \( \pi/k \) separation up to 7\( \text{GeV}/c \)
  - Time resolution < 20\( \text{ps} \)
  - Rate capability > 20\( \text{kHz}/\text{cm}^2 \)

This is big challenge of MRPC-TOF!!
How to reach high rate, high time

- Increase rate: decrease the resistivity of glass

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

- Improve TOF resolution
  - Reduce the width of gas gap
  - Improve precision of electronics

- Improve precision of electronics
  - High speed pulse sampling
  - Fast discriminator + high precision TDC

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Two technologies

Method 1: Time discrimination + TDC

- Preamplifier
- Slow shaper
- Fast shaper
- Discriminator
- TDC
- Slow ADC
- Amplitude
  - 60 MHz
  - 12 bit
- Time
- Noise of Disc
- Resolution of TDC
- Time precision

Method 2: Waveform digitization + Digital processing

- Preamplifier
- Fast FADC
- Digital Processing
- "Fast"
- 12 bit

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

Wang Yi, Tsinghua University 9th Workshop on Hadron Physics in China, July 24-28, 2017, Nanjing
M.C.S Williams’ work

M.C.S Williams, 24x160μm gaps, MRPC

MRPC is assembled with float glass, it’s rate <100 Hz/cm².
**EIC R&D Prototype MRPC**

<table>
<thead>
<tr>
<th></th>
<th>MRPC (C. Williams et al.)</th>
<th>MRPC (UIUC &amp; BNL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Gap Width</td>
<td>160um (fishing line)</td>
<td>105um (diameter of fishing line)</td>
</tr>
<tr>
<td># of Gas Gaps</td>
<td>4 stack x 6 gas gaps = 24</td>
<td>4 stack x 9 gas gaps = 36</td>
</tr>
<tr>
<td># of thin glass layers</td>
<td>4 stacks x 5 layers = 20 (250um thick glass)</td>
<td>4 stack x 8 layers = 32 (210um thick glass)</td>
</tr>
<tr>
<td>Preamplifier</td>
<td>Differential type, NINO chip (3GHz bandwidth)</td>
<td>TI LMH6554 2.8-GHz Evaluation Board</td>
</tr>
<tr>
<td>TDC and DAQ</td>
<td>Oscilloscope (Sampling speed of 10Gs)</td>
<td>DRS4-V5 (5 GSPS) + PC</td>
</tr>
<tr>
<td>Time resolution</td>
<td>30 ps with cosmic ray / 16 ps at T10 beam test CERN</td>
<td>??, Cosmic ray test / Beam halo test at COMPASS</td>
</tr>
</tbody>
</table>

- Narrower gap width -> fast charge dominant in the induced signal -> Better timing resolution
- Efficiency will be recovered by adding more gas gaps
Electronics development

Current test readout chain, using off the shelf electronic components
- Currently with DRS4, only 1-2 channels at a time can be read out
- Need 2 detectors for timing, reading out both ends, so test of 1 ch needs 4 readout ch

- Custom BNL fast preamp under testing, will help allow many more channels to be read

- DRS4 mRPC
- TI LMH5401EVM
- TI ADC-WB-BB (Balun)
- Hard metric 100Ω differential cables
- BNL “UFAMP” 4 channel 100Ω differential 900 MHz, 8x gain
Cosmic ray test

Cosmic rays
22kV
Efficiency

MRPC is assembled
with float glass, it's
rate <100 Hz/cm².
MRPC TOF wall we designed contain 150 MRPC modules in total, with 50 gas boxes and 3 counters in each box, covering the area of 10m².

Total channel ~3600
### Performance of low resistive glass

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>33 x27.6cm²</td>
</tr>
<tr>
<td>Bulk resistivity</td>
<td>$\sim 10^{10} \Omega \text{cm}$</td>
</tr>
<tr>
<td>Standard thickness</td>
<td>0.7, 1.1mm</td>
</tr>
<tr>
<td>Thickness uniformity</td>
<td>20μm</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</td>
</tr>
<tr>
<td></td>
<td>stable up to 1C/cm²</td>
</tr>
</tbody>
</table>

**Graph:**
- **X-axis:** Applied voltage (V)
- **Y-axis:** Bulk resistivity ($\Omega \text{cm}$)
- **Legend:**
  - 30°C
  - 40°C
  - 50°C
  - 60°C
  - 70°C

**Graph Description:**
- The graph shows the bulk resistivity of the glass at different temperatures (30°C, 40°C, 50°C, 60°C, 70°C) as a function of applied voltage.
- The resistivity is stable up to 1C/cm².
This glass was applied with 1000V for about 32 days, integrated charge: 1 C/cm$^2$ --roughly corresponding to the SoLID lifetime over 5 years operation at the maximum particle rate.

Aging test of the glass

**HV test on glass**

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**X ray irradiation**

**Neutron irradiation**
A $2^g$ MRPC prototype for SoLID-TOF

Volume resistivity: \(\sim 10^{10} \Omega \cdot \text{cm}\)

Material dimensions

<table>
<thead>
<tr>
<th>Material</th>
<th>Length/mm</th>
<th>Width/mm</th>
<th>Thickness/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas gap</td>
<td>-</td>
<td>-</td>
<td>0.25 \times 10</td>
</tr>
<tr>
<td>Inner glass</td>
<td>320</td>
<td>130-171</td>
<td>0.7</td>
</tr>
<tr>
<td>Outer glass</td>
<td>330</td>
<td>138-182</td>
<td>1.1</td>
</tr>
<tr>
<td>Mylar</td>
<td>335</td>
<td>153-198</td>
<td>0.18</td>
</tr>
<tr>
<td>Inner PCB</td>
<td>350</td>
<td>182-228</td>
<td>1.6</td>
</tr>
<tr>
<td>Outer PCB</td>
<td>350</td>
<td>172-218</td>
<td>0.8</td>
</tr>
<tr>
<td>Honeycomb</td>
<td>350</td>
<td>153-198</td>
<td>6</td>
</tr>
</tbody>
</table>

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Beam test @ Hall A

High Energy e- Beam

Target

Test setup

Target

PMT0
PMT1
PMT2
PMT3
PMT4

Shield

Top View

The diagram of DAQ system
Rate Performance

Voltage: 6800V

- Flux: 11 kHz/cm²
  - Efficiency: ~95%
  - Time Resolution: 78 ps

- Flux: 16 kHz/cm²
  - Efficiency: ~95%
  - Time Resolution: 82 ps

Wan Yi. A MRPC prototype for SOLID-TOF in Jlab.
2013_JINST_8_P03003
TOF readout chain with PADI and GET4

MRPC

Preamplifier & Discriminator

Time to Digital Converter

CLK

ROC

DCB

MRPC

CLK

TOF readout chain with PADI and GET4
## Design of $3^g$ 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 MRPC structure](image)
Test equipment

Gas box

Waveform Digitizer DT5742

- DRS4-V5 chip
- 16 channels
- 12bit 5GS/s
- 5 points for leading edge of MRPC

Fast amplifier
\[ \sigma_{MRPC} = \frac{\sigma_t}{\sqrt{2}} = \frac{40.91}{\sqrt{2}} = 28.93 \text{ps} \]
Next to do

- **NSFC key project:** Development of high rate and high time resolution TOF
  - Simulation to get: Width of gas gap $\rightarrow$ time resolution
  - Development of high rate 15ps resolution MRPC
  - Development of 15ps jitter SCA, fast amplifier and TDC
  - Impedance math

- **Study “ecological” gas mixture for high rate MRPC**
The “ecological” gas issue

- The European Community has prohibited the production and use of gas mixtures with Global Warming Power > 150 (GWP(CO$_2$) = 1)
  - This is valid mainly for industrial (refrigerator plants) applications
  - Scientific laboratories would be excluded
  - CERN could require to stick to these rules anyhow

- C$_2$H$_2$F$_4$ is the main component of the present RPC gas mixture:
  - GWP(C$_2$H$_2$F$_4$) = 1430, GWP(SF$_6$) = 23900, GWP(iC$_2$H$_{10}$) = 3.3

- C$_2$H$_2$F$_4$ and SF$_6$ crucial to ensure a stable working point in avalanche

- To test molecules similar to C$_2$H$_2$F$_4$ but with lower GWP
  - C$_3$H$_2$F$_4$ – tetrafluoropropene (GWP=4)
  - Should replace C$_2$H$_2$F$_4$ as automotive air-conditioning refrigerant

- Other possibility could be CF$_3$I – Trifluoriodomethane with GWP ~ 0 & ODP ~ 0
Possible eco-gas Replacements

Tetrafluorepropene (C₃H₂F₄)
It comes in two allotropic forms

HFO-1234ze

HFO-1234yf

<table>
<thead>
<tr>
<th>Molecule</th>
<th>CCl₂F₂</th>
<th>CF₄</th>
<th>R134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization energy (eV)</td>
<td>10.24</td>
<td>12.81</td>
<td>12.40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Molecule</th>
<th>R152a</th>
<th>HFO-1234ze</th>
<th>HFO-1234yf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization energy (eV)</td>
<td>10.78</td>
<td>9.34</td>
<td>9.37</td>
</tr>
</tbody>
</table>

Trifluoroiodomethane (CF₃I)

GWP and ODP close to 0

High quenching power
Very expansive! We were able to buy just a small bottle of 0.5 kg for very few preliminary tests

Molecule similar to R134a (C₂H₂F₄) BUT
HFO-1234 GWP=4
R134a GWP = 1430
HFO-1234yf HMIS code = 2
(moderate flammability)

In this talk we concentrate on HFO-1234ze
(HFO in the labels will mean HFO-1234ze)
**Title:** Replacing R134a with HFOze

**Diagram:**
- Efficiency
- Streamer probability

**Axes:**
- Efficiency (%)
- Streamer probability

**HV normalized to P=990 mbar and T= 20 °C**

**Legend:**
- CMS: R134a 95.2% iso 4.5% SF6 0.3%
- HFO 23.5% R134a 72% iso 4.2%, SF6 0.3%
- HFO 23.5% R134a 72% iso 4.5%
- HFO 45% R134a 50% iso 5%

**Institution:** INFN (Istituto Nazionale di Fisica Nucleare)

**Notes:**
- Test station

**Conference:** 9th Workshop on Hadron Physics in China, July 24-28, 2017, Nanjing
- Eco-gas candidate is 4-component mixture:
  - \( \text{CO}_2 / \text{HFOze} / \text{Isobutane} / \text{SF}_6 \)
Conclusions

• $3^g$ MRPC-TOF is high rate (20kHz/cm$^2$) and high time resolution (20ps).
  
  The time resolution of MRPC: <15ps
  Time jitter of electronics: <15ps
  This technology is a big challenge

• Search ecological gas mixture is meaningful and urgent
Thanks for your attention!