Development of Fast Timing Electronics for MRPC-TOF Detectors

Zhi Deng

Department of Engineering Physics, Tsinghua University, Beijing, China

Seminar Talk @ BNL Instrumentation Division, 9 June, 2010
Contents

• Introduction of MRPC detectors
• Current mode front end
• FPGA based Time to Digital Converter
MRPC: Timing RPC

- Large area, high granularity
- Good time resolution < 100 ps
- High efficiency > 95%

ALICE, STAR, FOPI, HADES HARP and CBM all use MRPCs to construct TOF system

The MULTIGAP Resistive Plate Chamber

Essentially a stack of resistive (glass) plates with electrodes stuck on the outside

Note 1: internal glass plates electrically floating - take and keep correct voltage by electrostatics and flow of electrons and ions produced in gas avalanches

Note 2: resistive plates transparent to fast signals - induced signals on external electrodes is sum of signals from all gaps
Different Prototypes

Used in HADEs

Used in STAR

Used in ALICE
<table>
<thead>
<tr>
<th>Detector</th>
<th>HARP</th>
<th>ALICE</th>
<th>STAR</th>
<th>FOPI</th>
<th>HADES</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(_{gaps})</td>
<td>4</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>gap size [mm]</td>
<td>0.3</td>
<td>0.25</td>
<td>0.22</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>gas[C(_2)F(_4)H(_2)/SF(_6)/C(_4)H(_10)]</td>
<td>90/5/5</td>
<td>90/5/5</td>
<td>95/0/5</td>
<td>85/10/5</td>
<td>98.5/1/0.5</td>
</tr>
<tr>
<td>electric configuration</td>
<td>cat-an-cat</td>
<td>cat-an-cat</td>
<td>an-cat</td>
<td>cat-an-cat</td>
<td>cat-an-cat</td>
</tr>
<tr>
<td>cell size [cm(\times)cm]</td>
<td>22(\times)10.6</td>
<td>2.5(\times)3.7</td>
<td>6.3(\times)3.1</td>
<td>90(\times)0.34</td>
<td>60(\times)2</td>
</tr>
<tr>
<td>detector size</td>
<td>10 m(^2)</td>
<td>150 m(^2)</td>
<td>60 m(^2)</td>
<td>5 m(^2)</td>
<td>8 m(^2)</td>
</tr>
<tr>
<td>N(_{channels})</td>
<td>368</td>
<td>160000</td>
<td>(\approx) 30000</td>
<td>5000</td>
<td>(\approx) 2100</td>
</tr>
<tr>
<td>HV/gap</td>
<td>3.0 kV</td>
<td>2.4 kV</td>
<td>2.35 kV</td>
<td>3.3 kV</td>
<td>3.2 kV</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>99%</td>
<td>99.9%</td>
<td>95-97%</td>
<td>97 (\pm) 3%</td>
<td>(&gt;95%)</td>
</tr>
<tr>
<td>plateau length</td>
<td>300 V</td>
<td>2000 V</td>
<td>500 V</td>
<td>600 V</td>
<td>(\geq) 200 V</td>
</tr>
<tr>
<td>(\sigma_T) (after slewing corr.)</td>
<td>150 ps</td>
<td>40 ps</td>
<td>60 ps</td>
<td>73 (\pm) 5 ps</td>
<td>70 ps</td>
</tr>
<tr>
<td>cross-talk/neighbor</td>
<td>&lt; 10%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>3-(\sigma) tails</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt; 2%</td>
<td>6%</td>
</tr>
<tr>
<td>space resolution [cm(^2)]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.6(\times)0.6</td>
</tr>
<tr>
<td>experiment rates</td>
<td>1 Hz/cm(^2)</td>
<td>50 Hz/cm(^2)</td>
<td>10 Hz/cm(^2)</td>
<td>50 Hz/cm(^2)</td>
<td>700 Hz/cm(^2)</td>
</tr>
<tr>
<td>dark rate [Hz/cm(^2)]</td>
<td>&lt; 0.1</td>
<td>-</td>
<td>&lt; 0.3</td>
<td>&lt; 1</td>
<td>2-3</td>
</tr>
<tr>
<td>rate capability [Hz/cm(^2)]</td>
<td>(\leq) 2000</td>
<td>(\leq)1000</td>
<td>-</td>
<td>-</td>
<td>350</td>
</tr>
<tr>
<td>(\rho d) [10(^{12}) (\Omega \times) cm(^2)]</td>
<td>10 (\times) 0.105</td>
<td>- (\times) 0.04</td>
<td>5 (\times) 0.055</td>
<td>- (\times) 0.15</td>
<td>5 (\times) 0.1</td>
</tr>
<tr>
<td>(q)</td>
<td>-</td>
<td>2 pC</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(q_{\text{prompt}})</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.7 pC</td>
</tr>
<tr>
<td>material budget ((x/X_\text{0}))</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12-24%</td>
</tr>
<tr>
<td>resistive material</td>
<td>float glass</td>
<td>float glass</td>
<td>float glass</td>
<td>float glass</td>
<td>float glass</td>
</tr>
</tbody>
</table>

MRPCs Used in Hadron Experiments
Only TPC:

\[ \frac{\pi}{k} \sim 0.7 \text{ GeV/c}, \]

\[ (\pi, k)/p \sim 1.1 \text{ GeV/c} \]

Only TOF:

\[ \pi /k \sim 1.6 \text{ GeV/c}, \]

\[ (\pi, k)/p \sim 3.0 \text{ GeV/c} \]
FAIR-CBM TOF

Heavy ion collision from 2-35 GeV

phase structure of strongly interacting baryon rich matter.

• Challenges:
  – high rate ≈ 20 kHz/cm²
  – good time resolution < 100 ps
  – large area and economic (price!)

• Solution:
  – low resistivity glass ~$10^{10}$ Ωcm
  – high rate MRPC (pad-readout and strip-readout)
High Rate MRPC

Ceramics

Semi-conductive glass

Float glass

Max Counting Rate (Hz/cm$^2$) vs. Volume Resistivity ($\Omega$ cm)

Beijing

INR+CBM

lip Coimbra

ALICE-muon

LHCb

ATLAS

Warsaw

CMS-forward

CMS-barrel

CERN+Bologna

CERN+Rio

Dresden

STAR

ALICE-TOF

Lip+USC

CBM Requirement

Streamers mode

Warm glass
Performance of High Rate MRPC

Efficiency and time resolution as a function of high voltage at a rate of about 800Hz/cm²

When the particle flux increases every 5 kHz/cm², the efficiency decreases by 1% and the time resolution deteriorates by 4 ps.
Requirements for Fast Electronics

- High bandwidth: multi-GHz, ~10ps time jitter
- Low power consumption: ~10mW/ch
- High rate: 20kHz/cm²

Multi-GHz bandwidth is needed for fully exploit the power of the detector.
Why Current Mode

• Information is represented by the branch currents rather than the nodal voltages
• Wide bandwidth, low input impedance
• Reduced dynamic power consumption
• Less sensitive to switching noise
• Better ESD immunity
• Lower supply voltage
Start from the discriminator

For a step input current

\[ Q_x = C_x \Delta V_x = i_s t + \int_{t}^{i} (i_{NM0} - i_{PM0}) dt \]

If \( i_{NM0} \) and \( i_{PM0} \) can be ignored During \( t \),

\[ t \approx \frac{Q_x}{i_s} \]

\[ \sigma_t = \frac{\sigma_{Q_x}}{i_s} = \frac{\sqrt{n e^2 t}}{i_s} = \frac{\sqrt{2i_n^2 t}}{i_s}, i_n^2 = \sum 4\gamma k T g_{mi} \]

\[ \sigma_t^2 = \frac{2i_n^2 Q_x}{i_s^3} \]

Minimum sized transistors are used for NM0 and PM0 and they are biased at very small current, so:

\[ \Sigma g_m \sim 1-100\mu S, \ C_x \sim 100fF, \ \Delta V_x \sim 0.1V, \ Q_x \sim 10fC \]

\[ \sigma_t \sim 0.5-4.7ps \text{ for } i_s = 10\mu A \]
Unfortunately

• Long connections between detectors and electronics
  → Parasitic capacitance at node $X$
• Also for fast signals, connections should be modeled as transmission line.
  → Need impedance matching: ~50 Ohm
    $$\Sigma g_m \sim 20 \text{mS}, \, Q_x \sim 10 \text{fC}$$
    $$\sigma_t \sim 66 \text{ps} \text{ for } i_s = 10 \text{µA}$$
  → Limited bandwidth, i.e., increase of $t$
    $$\Sigma g_m \sim 20 \text{mS}, \, Q_x \sim 10 \text{fC}$$
    $$d\sigma_t/dt \sim 33 \text{ps/ns} \text{ for } i_s = 10 \text{µA}$$
A Simple Current Mirror

For \( N=1 \), \( I_{bias}=3mA \), \( W1/L1=1500\mu/1\mu \)

\[ f_b = \frac{1}{2\pi\tau_b} = 510\text{MHz} \sim 1.4\text{GHz} \]

Current Gain = 1

\[ R_{in} = \frac{1}{g_{m1}} = \frac{1}{\sqrt{2\mu C_{ox} \frac{W}{L} I_D}} \]

\[ i_{out} = N \cdot i_s \]

\[ \tau_b = \frac{(C_{gs1} + C_{gs2} + C_{in})}{g_{m1}} \]

\[ i_{n,\text{out}}^2 = 4\gamma kT(N + N^2)g_{m1} \]
Time Jitter

\[ Q_x = \int_t i_s (1 - e^{-t/\tau_b}) dt = i_s t - i_s \tau_b (1 - e^{-t/\tau_b}) \]

for \( t \gg \tau_b \), \( Q_x \approx i_s t \), \( \sigma_t^2 = \frac{2i_n^2 Q_x}{i_s^3} \);

for \( t \ll \tau_b \), \( Q_x \approx \frac{i_s t^2}{2 \tau_b} \), \( \sigma_t^2 = \frac{\sqrt{2i_n^2}}{\sqrt{Q_x}} \left( \frac{\tau_b}{i_s} \right)^2 \)

\[ \sigma_t^2 = \frac{2 \cdot 4 \gamma kT(N + N^2) Q_x}{R_m (Ni_s)^3} \approx \frac{8 \gamma kTQ_x}{R_m Ni_s^3} \]

or

\[ \sigma_t^2 = \frac{\sqrt{2} \cdot 4 \gamma kT(N + N^2)}{\sqrt{Q_x}} \left( \frac{\tau_b}{Ni_s} \right)^2 \approx \frac{4\sqrt{2} \gamma kT(\frac{1}{\sqrt{N}} + \sqrt{N})}{\sqrt{Q_x}} \left( \frac{\tau_b}{i_s} \right)^2 \]
Seminar Talk @ BNL Instrumentation Division
Compared to voltage mode

\[ V_o = -\frac{A}{1+A} \frac{R_f}{1+sC_{in}\left(\frac{R_f}{1+A}\right)} \]

Gain = \( R_f C_{in} \)

\[ \tau_b = \frac{R_f C_{in}}{1+A} \]

\[ i_n^2 = \frac{(2\pi)^2 C_{in}^2 v_n^2 B_{eq}^2}{3} + \left(\frac{v_n^2}{R_f^2} + \frac{4kT}{R_f}\right) B_{eq}, \quad v_n^2 = \frac{4\gamma kT}{g_{m, in}} \]

\[ \sigma_i^2 = \frac{v_{on}^2}{k^2} = \frac{i_n^2 \cdot R_f^2}{\tau_b} e^{-t_0/\tau_b} \]

\[ = \frac{i_n^2 \tau_b^2}{i_s^2 e^{-2t_0/\tau_b}} \]
A Short Summary

• Using current mode, one can achieve:
  – ~10ps time jitter can be achieved for ~10µA input current
  – Current gain can help with time jitter performance if it is fast enough
  – Time jitter is not so sensitive to the input capacitance than voltage mode
Cascoding

For $N=1$, $I_{bias}=3mA$, $W1/L1=250u/1u$

$f_b = 1/(2\pi\tau_b) = 670MHz\sim1.76GHz$ @

Current Gain = 1
Cascoding with Current Feedback

\[ R_{in} = \frac{1}{(1+M)g_{m3}} \]

\[ i_{out} = \frac{N}{(1+M)} \cdot i_{in} \]

\[ \tau_{b1} = \frac{(C_{gs3} + C_{in})}{(1+M)g_{m3}}, \quad \tau_{b2} = \frac{(C_{gs1} + C_{gs2} + C_{gs4})}{g_{m1}} \]

\[ i_{in, out}^2 = 4\gamma kT[N^2g_{m3} + (N + N^2 + \frac{N^2}{M})g_{m1}] \]

For \( M=2, N=3 \), \( I_{bias}=1mA, W1/L1=250u/1u \)

\( f_b = \frac{1}{(2\pi\tau_b)} = 740MHz~2.2GHz \) @ Current Gain = 1
Chip Design

- Two different structures: cascoding and cascoding with current feedback
- 1-3mA static current per channel, $f_{-3dB} = 150$-$900$MHz @ $C_{in}=1pF$
- Very compact layout
Preliminary Test Results

• Static power consumption

![Graph showing linear relationships between bias current and power consumption](image)

- y = 0.1678x + 7.5316
  - R² = 0.9963
- y = 0.0692x + 3.1068
  - R² = 0.9963
Input Impedance - Static

Input Impedance test

$y = -5.6855 \ln(x) + 32.622$
$R^2 = 0.996$

$y = 43.075x^{-0.2668}$
$R^2 = 0.9956$

$y = 32.483x^{-0.2091}$
$R^2 = 0.9865$
Time Jitter vs. Input

Test @ Ibias=22\mu A
Power < 5mW/ch

- \(C_{\text{in}}=0\)
- \(C_{\text{in}}=50\text{pF}\)
- \(C_{\text{in}}=100\text{pF}\)
- \(C_{\text{in}}=470\text{pF}\)

\(~10\mu A\)  \(~100\mu A\)  55ps
Time Jitter vs. Cin

- $V_{in} = 20\text{mV}$
- $V_{in} = 22\text{mV}$
- $V_{in} = 50\text{mV}$
- $V_{in} = 100\text{mV}$
- $V_{in} = 200\text{mV}$

$C_{in}$ / pF

Time Jitter / ps

$V_{in} = 20\text{mV}$
$V_{in} = 22\text{mV}$
$V_{in} = 50\text{mV}$
$V_{in} = 100\text{mV}$
$V_{in} = 200\text{mV}$
High Resolution FPGA based TDC


Vernier caliper method


Delay chain method

2010/6/9
Implementation: Adder Carrier Chain

Signal in -> tap -> Signal out

2010/6/9 Seminar Talk @ BNL Instrumentation Division
Calibration

Signal Edge → Delay Cells → Count → RAM

Bin Width / ps vs Bin Code
Altera StratixII EP2S60F1020C3

Time Resolution

rms=38.7ps  two channels
rms=27.4ps  one channel
for bin width <50 ps
Wave Union TDC

First proposed by J. Wu and Z. Shi @ 2008 IEEE Nuclear Science Symposium
Calibration of Multi-Wave TDC

2010/6/9
Seminar Talk @ BNL Instrumentation Division
Improvement on Time Resolution

Compared to 10ps resolution using Altera Cyclone II EP2C8T144C6 by J. Wu @ 2008 IEEE NSS, Dresden

FWHM=26ps (rms=7.9ps for one channel)
Linearity: DNL

1LSB=41.8ps

1LSB=21.1ps

1LSB=14.2ps

1LSB=10.7ps

1LSB=8.5ps

1LSB=7.1ps
Linearity: INL

1LSB=41.8ps

1LSB=21.1ps

1LSB=14.2ps

1LSB=10.7ps

1LSB=8.5ps

1LSB=7.1ps

2010/6/9  Seminar Talk @ BNL Instrumentation Division
Resolution Dependence Puzzle

![Graph showing time difference and rms values over time]

- Time difference (ps)
- Rms (ps)

2010/6/9 Seminar Talk @ BNL Instrumentation Division
We assume that for the first order the delay chain stretches like a elastic band, so we can correct it by multiplying it by a coefficient
Real time Correction

- Add an additional delay chain to measure a fixed time delay generated by PLL and use it for bounce correction.
Corrected Results

2010/6/9 Seminar Talk @ BNL Instrumentation Division
Summary

• MRPC is the golden detector for ion particle TOF measurement. Time resolution of ~10ps can be achieved with ~10m^2 large area and low cost.

• Fast and low power consumption ASIC readout electronics are essential for fully exploit the power of the detectors. A current mode frontend and FPGA based TDC have been designed and tested.
Acknowledgements

• ASIC Group:
  Yinong Liu, Ji Qi, Jie Luo, Li He, Xuezhou Zhu

• MRPC Detector Group:
  Yi Wang, Qian Yue, Jingbo Wang

• National Science Foundation of China