FEE 2016 workshop Krakow

FE for time measurements

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Organization for Micro-Electronics desigN and Applications
INTRODUCTION

• Time resolution <50ps required by many experiments/applications keeping low power, large dynamic range ....

• **PET/ Time of Flight** measurements (SiPM)
  – Dynamic range: 1 pe (100fC) up to 3000 pe (300 pC)
  – Time resolution <100ps

• **CMS High Granularity CALorimeter**: (Si pin diodes)
  • Dynamic range EM showers: few fC up to ~10 pC (2500-5000 mips)
  • Calorimetry => Precision /linearity < 1%
  • Fast timing ability ~50ps (for > 10 mips desirable)
  • Peaking time 15-20 ns (minimize noise, minimise Out of Time pileup)
  • Power on detector < ~10 mW/channel all included
  • => see talk by Damien THIENPONT

• **ATLAS High Granularity Timing Detector** (LGAD or Si diodes)
  • Time performance ~30 ps: To reject Time Pile up events => better particle identification
  • Dynamic range: up to few Mips or 200Mips (depending on Preshower)
**Time walk and Time jitter**

**Time walk:** the voltage value $V_o$ is reached at different time for signal of different amplitudes.

**Jitter:** the noise is summed to the signal, causing amplitude variations.

$$\sigma_{TW}^2 = \left[ \frac{t_{rise}V_{th}}{S} \right]_{RMS}$$

Due to the physics of signal formation

$$\sigma_t^2 = \left( \frac{t_{rise}}{S/N} \right)^2 + \left[ \frac{t_{rise}V_{th}}{S} \right]_{RMS}^2 + \left( \frac{TDC_{bin}}{\sqrt{12}} \right)^2$$

Mostly due to electronic noise
Detector current

- **PIN diode**
  - $w = 200\mu m$
  - Very short rise time: $t_r \sim 10\text{ps}$
  - Relatively long «drift time»: $t_d \sim 2\text{ns}$

- **SiPM detector** (10pe-)
  - Very short rise time: $t_r \sim 10\text{ ps}$
  - Short duration: $t_d \sim 100\text{ps}$,
Detector impedance and input voltage

- 1 GHz, \( C_d = \) few tenths of pF, width of the input signal <1ns
- \( C_d > 1 \) pF, \( Z_s @ 1 \) GHz dominated by \( C_d \)
- Rise time: \( t_r = t_d \) when \( t_d \ll C_d R_s \) and \( t_r = C_d R_s \) when \( t_d \gg C_d R_s \)

![Diagram of detector circuit](image)

\[ V_{in} \] \[ V_{out} \]

- \( I_{in} \)
- width = \( t_d \)
- \( C_d = \frac{Q}{C_d} \) Charge sensitive
- \( V_{in(t)} \) if \( t_d \ll C_d R_s \)
- \( t_d \)
- \( C_d R_s \)
- max = \( C_d R_s \)
- \( V_{in(t)} \) if \( t_d \gg C_d R_s \)
- \( C_d R_s \)
- max = \( R_s I \) Current sensitive

\[ \begin{align*}
\text{Zs with } C_d \text{ in } // R_s = 50 \Omega & \quad 1 \text{ pF} \\
\text{Zs=47 } \Omega & \quad 10 \text{ pF} \\
\text{Zs=15 } \Omega & \quad 100 \text{ pF}
\end{align*} \]
Examples of pulse shapes

- SiPM pulse: $Q=160 \text{ fC}$, $C_d=100 \text{ pF}$, $L=0-10 \text{ nH}$, $RL=5-50 \text{ } \Omega$
- Sensitivity to parasitic inductance
- Choice of $RL$: decay time, stability
- Small $RL$ not necessarily the fastest
- Convolve with current shape… (here delta)

\[ \text{RC} \quad \text{L/R} \quad \frac{Q}{C_d} \]

\[ C=100 \text{ pF} \quad L=10 \text{ nH} \quad R=50 \text{ } \Omega \]

\[ C=100 \text{ pF} \quad L=10 \text{ nH} \quad R=5 \text{ } \Omega \]
HF configurations: CE and TZ

\[ \sigma_j^2 = \left( \frac{t_{\text{rise}}}{S/N} \right)^2 \]

CE

TZ

equivalent to

equivalent to
CE and TZ frequency response for Cd>>1pF

- **CE** using an OTA with gain $G_m$
  - $V_{out} = -G_m \left( Z_F // Z_L \right) V_{in}$

  With $Z_L$ neglected and $Z_s=C_d$ and $Z_F=R_F$
  - $V_{in} = Z_s I_{in} = \frac{1}{j\omega C_d} I_{in}$
  - $V_{out} = -G_m Z_F V_{in} = -\frac{G_m Z_F}{j\omega C_d} I_{in}$
  - $V_{out} = -G_m R_F \frac{Q_{in}}{C_d}$

  - $Z_{in} = Z_s \Rightarrow C_d$
  - $Z_{out} = Z_F = R_F$

- **TZ** using an OTA with gain $G_m$
  - $I_{out} = V_{out} / Z_L + (V_{out} - V_{in}) / Z_F$
  - $I_{in} = V_{in} / Z_s - (V_{out} - V_{in}) / Z_F$
  - $I_{out} = -G_m V_{in}$

  With $Z_L$ neglected and $Z_s=C_d$ and $Z_F=R_F$
  - $I_{in} = \frac{V_{in}}{Z_s} - I_{out}$
  - $V_{in} = \frac{1}{\frac{1}{Z_s} + G_m} \frac{1}{1+j\omega C_d} I_{in}$
  - $V_{out} = \left( 1 - G_m Z_F \right) V_{in}$
  - $V_{out} = \frac{1}{\frac{1}{G_m}} \frac{-R_F}{1+j\omega C_d} I_{in} \approx -G_m R_F \frac{I_{in}}{j\omega C_d} = -G_m R_F \frac{Q_{in}}{C_d}$

  - $Z_{in} = \frac{Q_m}{1+j\omega C_d} \Rightarrow 1 / G_m$ in // with $C_d$
  - $Z_{out} = \frac{R_F}{1+G_m R_F} \approx \frac{1}{G_m}$

@Nathalie Seguin-Moreau

C. de La Taille  FEE 2016 Krakow
CE and TZ: frequency and time response ($t_r$)

$$V_{out}(s) = -g_m (R_f \parallel C_p)V_{in}(s)$$

$$\frac{V_{out}(\omega)}{V_{in}(\omega)} = -g_m \frac{R_f}{j\omega C_p \left( R_f + \frac{1}{j\omega C_p} \right)} = \frac{-g_m R_f}{j\omega C_p R_f + 1}$$

$$BW_{ampli} = \frac{1}{2\pi R_f C_p} = \frac{0.35}{t_{r_{ampli}}}$$

$$\sigma^J_t = \frac{N}{dV}{dt} = \frac{t_r}{S}{N}$$

$$\frac{dV}{dt} \approx \frac{V_{\text{max}}}{\sqrt{t_{r_{ampli}}^2 + t_d^2}}$$

**Vout(t)**

- If $t_d >> t_r$ ampli
  - Rise time = $t_d$
  - $dV/dt = V_{\text{max}} / t_d$

- $V_{\text{max}} = -g_m R_p V_{\text{in}}$

**Vout(t)**

- If $t_d << t_r$ ampli
  - Rise time = $t_r$ ampli
  - $dV/dt = V_{\text{max}} / t_r$

- $V_{\text{max}} = -g_m R_p V_{\text{in}}$
• Similar noise for CE and TZ
• Parallel noise ($2qI_b$ or $2qI_G$) negligible at HF
• $\text{rms noise } v_n \text{ depends on the } \sqrt{\text{BW}}$
• Noise is independent of $C_d$
• But the signal is not independent of $C_d$
• $\text{S/N depends of } C_d \text{ and } \text{BW}$

$$V_{\text{OUT}} = -g_m R_f \frac{Q_{IN}}{C_d}$$

$$\frac{S}{N} \approx \frac{\alpha \sqrt{g_m}}{C_d \sqrt{\text{BW}}} \approx \alpha \frac{\sqrt{g_m} \sqrt{t_r \text{ ampli}}}{C_d}$$
Choice of preamp tr: Jitter, Time Walk, td compromise

\[
\sigma_t^J = \frac{N}{dV} = \frac{N}{S} = \sqrt{\frac{t_{r-a}^2 + t_d^2}{S}} = \alpha \frac{\sqrt{t_{r-a}^2 + t_d^2}}{\sqrt{g_m}} = \alpha \frac{C_d}{\sqrt{g_m}} \frac{\sqrt{t_{r-a}^2 + t_d^2}}{\sqrt{t_{r-a}}}
\]

Optimum value: \( t_{r-a} = t_d \)

Detector thickness: 100 micron
Collection Time = 1250 ps

@Nicolo Cartiglia, INFN Torino
Vin and Vout CE, TZ Cd=10pF td=10ps 1fC

Transient Response

Cd=10pF
td=10ps
lin=100µA
Qin=1fC
Output noise CE and TZ for Cd = 10pF 100pF

Noise Response

<table>
<thead>
<tr>
<th>Name</th>
<th>Vs</th>
<th>CE 10pF</th>
<th>CE 100pF</th>
<th>TZ 10pF</th>
<th>TZ 100pF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **CE**
  - 10pF: M34: 168.370MHz 17.775nV/sqrt(Hz)
  - 100pF: M35: 1.00904GHz 14.495nV/sqrt(Hz)

- **TZ**
  - 10pF: M39: 117.31MHz 18.4997nV/sqrt(Hz)
  - 100pF: M40: 978.36MHz 16.185nV/sqrt(Hz)
CE and TZ in TSMC 65 nm comparison

- TZ faster than CE but possibly unstable => CE looks better
- Normalization to 1 fC, square pulse. Noise optimistic due to bad design kit

<table>
<thead>
<tr>
<th></th>
<th>CE 10pF</th>
<th>TZ 10pF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10ps 1fC</td>
<td>out=3.95mV</td>
<td>out=3.3 mV</td>
</tr>
<tr>
<td></td>
<td>tr=250ps</td>
<td>tr=154ps</td>
</tr>
<tr>
<td></td>
<td>BWa=1.4GHz</td>
<td>BWa=2.3 GHz</td>
</tr>
<tr>
<td></td>
<td>rms=0.85mV</td>
<td>rms=0.96mV</td>
</tr>
<tr>
<td></td>
<td>S/N=4.6</td>
<td>S/N=3.4</td>
</tr>
<tr>
<td></td>
<td>$\sigma_j=250ps/4.6=54$ ps</td>
<td>$\sigma_j=154ps/3.4=45$ ps</td>
</tr>
<tr>
<td>td=1ns</td>
<td>out=3.55mV</td>
<td>out=2.34mV</td>
</tr>
<tr>
<td>Qin= 1µA.1ns=1fC</td>
<td>tr=800ps</td>
<td>tr=740ps</td>
</tr>
<tr>
<td></td>
<td>BWa=1.4GHz</td>
<td>BWa=2.3 GHz</td>
</tr>
<tr>
<td></td>
<td>rms=0.85mV</td>
<td>rms=0.96mV</td>
</tr>
<tr>
<td></td>
<td>S/N=4.2</td>
<td>S/N=2.4</td>
</tr>
<tr>
<td></td>
<td>$\sigma_j=800ps/4.2=190$ ps</td>
<td>$\sigma_j=740ps/2.4=300$ ps</td>
</tr>
<tr>
<td>td=1ns and tr_ampli=td</td>
<td>out=3.47mV (CL=100fF)</td>
<td>out=857 µV (Cf=600fF)</td>
</tr>
<tr>
<td>Qin= 1µA.1ns=1fC</td>
<td>tr=1.1ns</td>
<td>tr=1040 ps</td>
</tr>
<tr>
<td></td>
<td>BWa=440MHz</td>
<td>BWa=450MHz</td>
</tr>
<tr>
<td></td>
<td>rms=0.45mV</td>
<td>rms=136 µV</td>
</tr>
<tr>
<td></td>
<td>S/N=7.7</td>
<td>S/N=6.3</td>
</tr>
<tr>
<td></td>
<td>$\sigma_j=1100ps/7.7=143$ ps</td>
<td>$\sigma_j=1040ps/2.4=165$ ps</td>
</tr>
</tbody>
</table>
CE in SiGe 130nm and in TSMC 130 nm

- Broad Band amplifier CE configuration
- Same current ($I_c=700 \, \mu A$), same $R_f=4K$, $v_{dd}=1.2V$
- Higher gain with SiGe but larger noise due to $r_{bb'}$

<table>
<thead>
<tr>
<th>CE 10pF</th>
<th>TSMC 130 nm</th>
<th>CE 10pF</th>
<th>SiGe 130nm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>td=10ps</strong></td>
<td><strong>out=3.7mV</strong></td>
<td><strong>out=8.95 mV</strong></td>
<td></td>
</tr>
<tr>
<td>$Q_{in}=I_{in}.t_d=100\mu A.10ps=1fC$</td>
<td>$tr=220ps$</td>
<td>$tr=176 ps$</td>
<td></td>
</tr>
<tr>
<td>$B_Wa=1.6 \text{GHz}$</td>
<td>$\text{rms}=1.3 \text{ mV}$</td>
<td>$\text{rms}=3.14mV$</td>
<td></td>
</tr>
<tr>
<td>$S/N=2.8$</td>
<td>$\sigma_j=220ps/2.8=78 \text{ ps}$</td>
<td>$S/N=2.85$</td>
<td></td>
</tr>
<tr>
<td><strong>td=1ns and tr_ampli=td</strong></td>
<td><strong>out=3.52mV(CL=100fF)</strong></td>
<td><strong>out=7.5mV (CL=110fF)</strong></td>
<td></td>
</tr>
<tr>
<td>$CL=100fF$</td>
<td>$tr=1.1ns$</td>
<td>$tr=1.1 \text{ ns}$</td>
<td></td>
</tr>
<tr>
<td>$Q_{in}= 1\mu A.1ns=1fC$</td>
<td>$B_Wa=440MHz$</td>
<td>$B_Wa=440MHz$</td>
<td></td>
</tr>
<tr>
<td>$\text{rms}=0.66mV$</td>
<td>$S/N=5.3$</td>
<td>$\text{rms}=1.4 \text{ mV}$</td>
<td></td>
</tr>
<tr>
<td>$\sigma_j=1100ps/5.3=206 \text{ ps}$</td>
<td>$\sigma_j=1.1\text{ns}/5.4=204 \text{ ps}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
20pF → 2pF:

Signal = \frac{Q_{IN}}{C_d} \times 10

I/10 \Rightarrow \sqrt{g_m} \text{ divided by } \sqrt{10}

\Rightarrow \frac{S}{N} \times \sqrt{10}

\frac{S}{N} \approx \frac{\alpha \sqrt{g_m}}{C_d \sqrt{\frac{1}{BW}}} \approx \alpha \frac{\sqrt{g_m} \sqrt{t_{\text{ampi}}}}{C_d}
CE in TSMC 130 nm: jitter vs tr (BW) and td

- With I source trans (0 for 2 pF or 1.8mA for 20pF)
- Follower (connected to a discriminator)

\[
\sigma_t^J = \frac{N}{dV} = \frac{t_r}{S} = \sqrt{\frac{t_{r_{\text{ampli}}}^2 + t_d^2}{N}}
\]

**POWER: 0.5mW/ mm²**

<table>
<thead>
<tr>
<th>CE</th>
<th>Cd=2pF (Id=220 µA)</th>
<th>Cd=20pF (Id=2.1 mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>td=10ps</strong></td>
<td>out = 6.9 mV</td>
<td>out=3.37 mV</td>
</tr>
<tr>
<td>Qin=lin.td= 100µA.10ps=1fC</td>
<td>out_fol=6.1 mV</td>
<td>out_fol=3.1 mV</td>
</tr>
<tr>
<td></td>
<td>tr_fol=284 ps</td>
<td>tr_fol=290 ps</td>
</tr>
<tr>
<td></td>
<td>BWa=1.2 GHz</td>
<td>BWa=1.2 GHz</td>
</tr>
<tr>
<td></td>
<td>rms=0.485 mV</td>
<td>rms=1.2 mV</td>
</tr>
<tr>
<td></td>
<td>S/N=12.6</td>
<td>S/N=2.6</td>
</tr>
<tr>
<td></td>
<td>(\sigma_j=284\text{ps}/12.6=23 \text{ps})</td>
<td>(\sigma_j=290\text{ps}/2.6=110 \text{ps})</td>
</tr>
<tr>
<td><strong>td=1ns and tr_ampli=td</strong></td>
<td>out=6.4 mV</td>
<td>out=3.2 mV</td>
</tr>
<tr>
<td>CL=100fF</td>
<td>out_fol=5.9 mV</td>
<td>out_fol=3.05 mV</td>
</tr>
<tr>
<td>Qin= 1µA.1ns=1fC</td>
<td>tr_fol=1.1 ns</td>
<td>tr_fol=1.1 ns</td>
</tr>
<tr>
<td></td>
<td>BWa=410 MHz</td>
<td>BWa=440 MHz</td>
</tr>
<tr>
<td></td>
<td>rms=0.39 mV</td>
<td>rms=0.8mV</td>
</tr>
<tr>
<td></td>
<td>S/N=15</td>
<td>S/N=3.8</td>
</tr>
<tr>
<td></td>
<td>(\sigma_j=1.1\text{ns}/15=73 \text{ps})</td>
<td>(\sigma_j=1.1\text{ns}/3.8=288 \text{ps})</td>
</tr>
</tbody>
</table>
### SIMULATIONS WITH DELAY LINE

- Sensors 3x3 mm² – Chip 64 channels, 8x8 sensors
  => ≈2.5x2.5 cm²
- Max distance pixel-FE input: 2.5 cm x √2 = 3.5 cm
  => td = 3.5 cm x 5 ns/m = 175 ps

<table>
<thead>
<tr>
<th>CE</th>
<th>Cd=20pF (Id=2.1 mA)</th>
<th>With delay line</th>
</tr>
</thead>
</table>
| td=10ps | Qin=lin.td= 100μA.10ps=1fC | out=3.37 mV  
out_fol=3.1 mV  
tr_fol=290 ps  
BWa=1.2 GHz  
rms=1.2 mV  
S/N=2.6  
σj=290ps/2.6=110 ps | out=4.87 mV  
out_fol=4.26 mV  
tr_fol=228 ps  
BWa=1.5 GHz  
rms=1.25 mV  
S/N=3.4  
σj=228ps/3.4=67 ps |

<table>
<thead>
<tr>
<th>td=1ns and tr_ampli=td</th>
<th>CL=100fF</th>
<th>Qin= 1μA.1ns=1fC</th>
</tr>
</thead>
</table>
|                        | out=3.2 mV  
out_fol=3.05 mV  
tr_fol=1.1 ns  
BWa=440 MHz  
rms=0.8mV  
S/N=3.8  
σj=1.1ns/3.8=288 ps | out=2.86 mV  
out_fol=2.70 mV  
tr_fol=950 ps  
BWa=440 MHz  
rms=0.83mV  
S/N=3.2  
σj=950ps/3.2=290 ps |
PETIROC2 DESCRIPTION

- Time of Flight read-out chip with embedded TDC (25 ps bin) and ADC
- Dynamic range: 160 fC up to 400 pC
- 32 channels (negative input)
  - 32 trigger outputs
  - NOR32_chrage
  - NOR32 time
  - Charge measurement over 10 bits
  - Time measurement over 10 bits
  - One multiplexed charge output
- Common trigger threshold adjustment and 6bit-dac/channel for individual adjustment
- Variable shaping time of the charge shaper
- 32 8bit-input dac for SiPM HV adjustment
- Power consumption 6 mW/ch
- Front-end
  - Broad Band SiGe fast amplifier
  - Fast SiGe discriminator
  - 1 GHz overall bandwidth, gain = 20
PETIROC2A: Rise Time of the PA+discriminator

- Injection of a step of 2 mV in ch20, reconstruction of pulse by discriminator
- The picosecond generator: \( tr_{10\%-90\%} = 300 \text{ ps} \), \( BW = 0.35/tr \sim 1 \text{ GHz} \)
- Can also use \( BW = 0.1/(t_{50\%}-t_{10\%}) \)
PETIROC2A: SCURVES

- Injection of a step (1mV, 2mV, 3mV, 4mV, 5mV and 10mV)
- With clocks and without clocks.
- Noise without clock : 2.2 mV rms (100uV referred to the input)
PETIROC2A: JITTER MEASUREMENT

- Jitter vs threshold & injection, Jitter improves with signal
- Clock couplings: through substrate, better results expected with technologies that offer triple well trans (TSMC 130nm)
- jitter<40 ps for injected charge >1pe (= 1mV at the input)

\[
1\text{pe} \sim 1\text{mV}
\]

\[
\frac{100\text{fC}}{100\text{pF}} = 1\text{mV}
\]
PETIROC2A: TIME WALK

- Discriminator output
- Time walk < 350ps

\[ 1 \text{pe} \sim 1 \text{mV} \]

\[ \frac{100 \text{fC}}{100 \text{pF}} = 1 \text{mV} \]
ToT and charge measurement

- Discriminator width for time walk correction
- Charge measurement up to 300 pC for energy measurement
  - +/- 2 LSB INL on 10bit internal ADC
PETIROC2A: TAC

- 160MHz clock seen on the TDC (residuals).
- Rms of the histogram of the residuals: 2.6 ADC units
  \[ \Rightarrow \text{Time resolution: } 2.6 \times 36 \text{ ps (step)} = 90 \text{ ps rms} \]
- Need to calibrate offset and slope per channel
**Electrical tests for RPC**

Currently, 19 channels are implemented on the FPGA → measurement of 8 strip, with two channels per strip.

Measurement of both strip’s ends via 2 channels of the same PETIROC ASIC.

Corresponding discriminator outputs of ASIC is sent to a TDC on FPGA (Altera Cyclone II)

\[ \sigma_t \approx 20-30 \text{ ps} \]
CONCLUSIONS

- High speed preamplifiers: similar performance broadband/transimpedance
  - Electronics contribution to jitter: \[ \sigma_t^J \approx \alpha C_d \sqrt{\frac{t_d}{g_m}} \]
  - Jitter deeply dependent on detector capacitance and time duration
    - \( C_d \): must be as small as possible to have a large input signal: \( V_{in} = Q_{in}/C_d \)
      \( \Rightarrow \) Try to optimize thickness and area of the sensor taking into account the radiation hardness and the minimization of the drift time (the larger the drift time, the larger the jitter)
    - Preamp bandwidth should match signal duration
    - Preamp transconductance \( g_m \) determines noise, scaling as \( \sqrt{I_d} \)
  - Time walk correction to be done: Time Over Threshold (TOT), Constant Fraction Discriminator
  - Will be tested for ATLAS HGTDT in TSMC130nm in the fall

- PETIROC2 = 1 GHz Broadband amplifier + discriminator
  - Petiroc2 with external TDC resolution ~20 ps
  - Petiroc2 with internal TAC: resolution ~100ps
<table>
<thead>
<tr>
<th>Chip</th>
<th>Detector</th>
<th>Ch</th>
<th>Polarity</th>
<th>Dyn Range</th>
<th>Specificities</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAROC</td>
<td>PM</td>
<td>64</td>
<td>&lt;0</td>
<td>5 fC - 5 pC</td>
<td>64 trig outputs, internal 8/10/12-bit ADC (for charge measurement)</td>
</tr>
<tr>
<td>SPACIROC</td>
<td>PM</td>
<td>64</td>
<td>&lt;0</td>
<td>2 pC- 220 pC</td>
<td>Fast photon counting (50MHz)</td>
</tr>
<tr>
<td>PARISROC</td>
<td>PM</td>
<td>16</td>
<td>&lt;0</td>
<td>50 fC - 100 pC</td>
<td>Internal TDC (&lt;1ns), 16 trig outputs</td>
</tr>
<tr>
<td>HARDROC</td>
<td>RPC</td>
<td>64</td>
<td>&lt;0</td>
<td>2 fC - 10 pC</td>
<td>3 discriminators, 128 deep digital memory to store 2x64 discriminator encoded data</td>
</tr>
<tr>
<td>MICROROC</td>
<td>μMEGAS/GEM</td>
<td>64</td>
<td>&lt;0</td>
<td>0.2 fC - 500 fC</td>
<td>3 discriminators, 128 deep digital memory to store 2x64 discriminator encoded data</td>
</tr>
<tr>
<td>SKIROC</td>
<td>Si pin diodes</td>
<td>64</td>
<td>&gt;0</td>
<td>0.3 fC - 10 pC</td>
<td>Internal 12-bit ADC for charge measurement</td>
</tr>
<tr>
<td>SPIROC</td>
<td>SiPM</td>
<td>36</td>
<td>&gt;0</td>
<td>10 fC - 300 pC</td>
<td>36 HV SiPM tuning (8 bits), Internal 12-bit ADC for charge and time measurement</td>
</tr>
<tr>
<td>EASIROC</td>
<td>SiPM</td>
<td>32</td>
<td>&gt;0</td>
<td>10 fC - 300 pC</td>
<td>32 HV SiPM tuning (8 bits), 32 trigger outputs</td>
</tr>
<tr>
<td>CITIROC</td>
<td>SiPM</td>
<td>32</td>
<td>&gt;0</td>
<td>10 fC - 300 pC</td>
<td>32 HV SiPM tuning (8 bits), 32 trigger outputs</td>
</tr>
<tr>
<td>PETIROC</td>
<td>SiPM</td>
<td>32</td>
<td>&lt;0</td>
<td>100fC – 300 pC</td>
<td>32 HV SiPM tuning (8 bits), 32 trigger outputs, Internal 10-bit ADC for charge and time measurement (25 ps)</td>
</tr>
<tr>
<td>TRIROC</td>
<td>SiPM</td>
<td>64</td>
<td>Both</td>
<td>100 fC- 300 pC</td>
<td>64 HV SiPM tuning (8 bits), 64 trigger outputs, Internal 10-bit ADC for charge and time measurement (25 ps)</td>
</tr>
</tbody>
</table>
SIMULATIONS WITH DELAY LINE

- LGAD sensor 100um
- 1MIP=6 fC Cd 20pF

- Sensors 3x3 mm2 – Chip 64 channels, 8x8 sensors => ≈2.5x2.5 cm2 => Max distance: 2.5cm x√2=3.5 cm => td=3.5cmx5ns/m= 175 ps

<table>
<thead>
<tr>
<th>CE</th>
<th>Cd=20pF (Id=2.1 mA)</th>
<th>With delay line</th>
</tr>
</thead>
<tbody>
<tr>
<td>tr=500ps tf=700ps Qin=6fC</td>
<td>out_fol=19 mV</td>
<td>out_fol=16.9 mV</td>
</tr>
<tr>
<td></td>
<td>tr_fol=708ps</td>
<td>tr_fol=480ps</td>
</tr>
<tr>
<td></td>
<td>BWa=1.2 GHz</td>
<td>BWa=1.2 GHz</td>
</tr>
<tr>
<td></td>
<td>rms=1.18 mV</td>
<td>rms=1.24 mV</td>
</tr>
<tr>
<td></td>
<td>S/N=16</td>
<td>S/N=13.6</td>
</tr>
<tr>
<td></td>
<td>σj=708ps/16=44 ps</td>
<td>σj=480ps/13.6=35 ps</td>
</tr>
<tr>
<td>tr_ampli=td CL=100fF Qin=6fC</td>
<td>out_fol=18.7 mV</td>
<td>out_fol=16.3 mV</td>
</tr>
<tr>
<td></td>
<td>tr_fol=1.05 ns</td>
<td>tr_fol=1.0 ns</td>
</tr>
<tr>
<td></td>
<td>BWa=440 MHz</td>
<td>BWa=440 MHz</td>
</tr>
<tr>
<td></td>
<td>rms=0.8 mV</td>
<td>rms=0.8 mV</td>
</tr>
<tr>
<td></td>
<td>S/N=23.4</td>
<td>S/N=20.3</td>
</tr>
<tr>
<td></td>
<td>σj=1.05ns/23.4=45 ps</td>
<td>σj=1.0ns/20.3=49 ps</td>
</tr>
</tbody>
</table>
Injecting charge on test points and then recording time difference $\Delta T = T_2 - T_1$.

$\sigma_t \approx 20$-$30$ ps
Timing performance

Same measurements but with more precise generator

<table>
<thead>
<tr>
<th>Strip</th>
<th>Jitter rms (charges injected = 5pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0.0347</td>
</tr>
<tr>
<td>18</td>
<td>0.03162</td>
</tr>
<tr>
<td>20</td>
<td>0.03355</td>
</tr>
<tr>
<td>22</td>
<td>0.03445</td>
</tr>
<tr>
<td>24</td>
<td>0.03479</td>
</tr>
<tr>
<td>26</td>
<td>0.03567</td>
</tr>
<tr>
<td>28</td>
<td>0.03467</td>
</tr>
<tr>
<td>30</td>
<td>0.03443</td>
</tr>
</tbody>
</table>

Test are being performed on:
- ASIC configuration for optimal lower charge performance
- TDC time evolution with different injection points of the strip

Next step to use the board on a detector.
LGAD SIGNAL

Gain electron: absorbed immediately
Gain holes: long drift home

Electrons multiply and produce additional electrons and holes.
- Gain electrons have almost no effect
- Gain holes dominate the signal

➔ No holes multiplications
CE in TSMC 130 nm: jitter vs tr (BW) and td

- Simulations for Cd=2pF and 20pF
- Normalization made with LGAD pulse shape and 1 MIP = 6fC
- 20pF → 2pF: Signal=Qin/Cd x 10 and I/10 => √gm divided by √10 => S/N x √10

\[ \sigma_j = \frac{\sigma_N}{C_d \sqrt{BW}} \approx \frac{\alpha \sqrt{g_m}}{C_d \sqrt{BW}} \]

**POWER: 0.5mW/ mm2**

<table>
<thead>
<tr>
<th>CE</th>
<th>Cd=2pF (I_d=220 µA)</th>
<th>Cd=20pF (I_d=2.1 mA)</th>
</tr>
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<tbody>
<tr>
<td>tr=500ps tf=700ps Q_in=6fC</td>
<td>out_fol=36.6 mV tr_fol=700 ps BWA=1.1 GHz rms=0.485 mV S/N=75 σ_j=700ps/75=10 ps</td>
<td>out_fol=19 mV tr_fol=708ps BWA=1.2 GHz rms=1.18 mV S/N=16 σ_j=708ps/16=44 ps</td>
</tr>
<tr>
<td>tr_ampli=td CL=100fF Q_in=6fC</td>
<td>out_fol=35.7 mV tr=1.1 ns BWA=410 MHz rms=0.39 mV S/N=92 σ_j=1.1ns/92=12 ps</td>
<td>out_fol=18.7 mV tr_fol=1.05 ns BWA=440 MHz rms=0.8 mV S/N=23.4 σ_j=1.05ns/23.4=45 ps</td>
</tr>
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</table>
lin LGAD: WFM with 2 and 20pF

20pF → 2pF:

Signal = \frac{Q_{in}}{C_d} \times 10

I/10 => \sqrt{gm} divided by \sqrt{10}
SIMULATIONS WITH DELAY LINE

- 1MIP=6 fC Cd 20pF

- Sensors 3x3 mm² – Chip 64 channels, 8x8 sensors => ≈2.5x2.5 cm² => Max distance: 2.5 cm x √2 = 3.5 cm => td=3.5 cm x 5 ns/m = 175 ps

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• Injection of a step
  ⇒ out\_RF = E0(1-e-t/τ)
  ⇒ BW = 0.1/ Δt\_{10\% - 50\%}
    – Simul of PA alone : BW= 6 GHz
    – Indirect measurement at discrim output
    – Threshold set at 10 and 50\% of the pa output

• Measurement:
  BW of PA+discr\_output > 1GHz
  ⇒ tr (amplifier) < 300ps