Towards a 4\textsuperscript{th} dimensional tracker system

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Outline

- **Introduction, Motivation & challenges for a 4th dimensional tracker system:**
  - Timing detectors in current and recent experiments.
  - The NA62 Gigatracker: a stepping stone towards a true 4th dimensional tracking.
  - Timing layers and particle-flow calorimeters at HL-LHC
  - Timing at the Future Circular Collider.

- **Sensors for timing 101:**
  - timing basics Silicon
  - Silicon diode detectors cases of use.

- **Inverse-Low Gain Avalanche Detectors (ILGAD): A sensor for a large-scale high-precision 4th dimensional tracker system.**
  - Technology description.
  - Performance of proof-of-concept prototype
Timing detectors: the recent past (1)

- Precise time stamping of charged particles ($\Delta t \geq 100$ ps) by dedicated Time-of-Flight (ToF) detectors.
- **Particle ID** of low momentum charged particles (mostly pion/kaon disentangling in flavor physics experiments)
- ToF detector determines speed of a charged particle by measuring flight time $t$ across a known distance $L$. Knowing the particle momentum $p$, one determines the mass.

$$m = \frac{p}{c} \sqrt{\frac{c^2 t^2}{L^2}} - 1$$

**Mass vs momentum**

CDF-II ToF detector at Tevatron
Timing detectors: the recent past (2)

- Fast detection sensing technologies:
  - Fast scintillators + conventional Photomultiplier Tubes
  - Resistive Plate Chambers (very large area detectors).
- Limitations:
  - Difficult to go below 100 ps timing resolution, severe gain reduction inside magnetic fields (PMT), bulky, scintillator and gaz radiation-induced aging, limited granularity (spatial resolution).

CDF & Belle ToF Detectors
Overall Time resolution
~ 100 ps

ALICE ToF detector
Overall time resolution
~ 120 ps
GigaTracker: A true 4th dimensional tracker

- Aim to measure $\text{Br}(K^+ \pi^+ \nu \nu)$ SM branching fraction very small $\sim 10^{-10}$
- Unstructured particle beam with $\sim 5$ second burst every $\sim 42$ seconds (instantaneous rate 750 MHz)

Hybrid pixel detector:
- 300 um $\times$ 300 um pixels
- One sensor ($\sim 6 \times 3 \text{ cm}^2$) bump-bonded to 10 read-out chips
Motivation: Why do we need precise time stamping of particles? (1)

- Future hadronic colliders (HL-LHC, FCC) to increase many fold the current LHC luminosity: track multiplicity and bias events

Thousands of tracks, vertices, calorimeter clusters that must be disentangled and accurately determined
Motivation: Why do we need precise time stamping of particles? (2)

- Profit from primary vertices' time spread.

- With a time spread ~ 200ps then 20-30 ps of PV timing resolution is required to disentangle the different primary vertices.
Motivation: Why do we need precise time stamping of particles? (3)

- Suppression of mismatched PU tracks, Jet pileup and improved of track isolation.
Sensors for timing: Basics
Here focus on sensor’s contribution: dominated by jitter and time walk (pulse amplitude and leading edge distortion)

\[ \sigma_t = \frac{\sigma_V}{dV/dt} \quad \frac{dV}{dt} \approx \frac{V}{t_r} \quad \Rightarrow \quad \sigma_t = \frac{t_r}{SNR} \]

Rise time limited by bandwidth (partially due to sensor’s capacitance)

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Silicon-based sensors timing

- Silicon-based diodes provide both fast rise time and relative large signal/noise ratio.
- Three operating modes: no signal gain (PIN), proportional (APD) and Geiger mode (SiPMT).

\[1\] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006
Timing with PIN diodes : CMS HGCAL as case of use

- Very reliable and mature mass production technology
- Main limitation: low SNR

Scintillator + SiPM

PIN SILICON DIODES,
active thickness 300, 200, 100 µm

PIN SILICON DIODES,
active thickness 300, 200, 100 µm
Avalanche mode diode (Low Gain Avalanche Detector - LGAD): Case of use ETL at CMS

- Main advantage: custom SNR for optimal for timing and tracking
- Main limitation: moderated radiation tolerance and yet to demonstrate as mass-scale production technology.
Silicon Photomultipliers: (Geiger-mode APD)

Case of use: BTL detector at CMS

- Mature technology, mass produced and cheap sensing element.
- Main limitation: moderate radiation tolerance < $2 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$ and concept with intrinsic poor spatial resolution.
## Silicon–based timing: Performance Comparison

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>RISE – TIME (DRIVEN BY CAPACITANCE)</th>
<th>SNR</th>
<th>RADIATION TOLERANCE</th>
<th>MASS PRODUCTION (AFFORADABLE)</th>
<th>DRIVING LIMITATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PIN</strong> (NO GAIN)</td>
<td>FAST &lt; 1ns</td>
<td>LOW</td>
<td>HIGH</td>
<td>POSSIBLE</td>
<td>LOW SIGNAL</td>
</tr>
<tr>
<td><strong>LGAD</strong> (PROPORTIONAL GAIN)</td>
<td>FAST &lt;1ns</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
<td>POSSIBLE TO BE DEMONSTRATED</td>
<td>RADIATION TOLERANCE</td>
</tr>
<tr>
<td><strong>SIPM</strong> (GEIGER MODE)</td>
<td>FAST &lt;1ns</td>
<td>VERY HIGH</td>
<td>MEDIUM</td>
<td>POSSIBLE</td>
<td>RADIATION TOLERANCE &amp; POOR SPATIAL RESOLUTION</td>
</tr>
</tbody>
</table>
Inverse-Low Gain Avalanche Detector
a full fledged 4th dimensional sensor
**I-LGAD basics: a 4\textsuperscript{th} dimensional tracking sensor**

Multiplication layer divided into strip  
Collects negative carriers (e)  
Simple single side process

Multiplication layer extended over the electrode  
Collects positive carriers (h)  
Complex double side process

**LGAD**  
N on P microStrip

**P on P microStrip**  
**iLGAD**

![Diagram](image)

- **Passivation**  
- **Aluminum**  
- **N+ Cathode**  
- **P-Stop**  
- **P-Multiplication**
I-LGAD basics: multiplication footprint

- Distinct signature of signal amplification: cathode illumination with red laser
- Injections of electron into the cathode, resulting transient current is a sequential contribution of primary electrons reaching the amplification layer and secondary holes drifting towards the anode.
Gain Spatial Uniformity: the fill factor issue

- Conventional LGAD: multiplication layer interspace presents reduced/suppressed gain.

Back-side red laser scanning transversal to the strip direction

Signal depts between the Strips (no multiplication layer)

- I-LGAD: non-segmented multiplication layer should present uniform gain.
Gain Spatial Uniformity: Validation with MIPs


Strip LGAD

I-LGAD
(8533W1K05T, 45 strips 160 um, non-irradiated)
Gain Spatial Uniformity: Collected Charge

LGAD

Peak 1: 24 Kelectrons
Peak 2: 65 Kelectrons

i-LGAD

Peak: 76 Kelectrons

Standard PIN

Peak: 24 Kelectrons
Gain Spatial Uniformity: Gain vs. Hit position (1)

- Dependence of the Signal-to-Noise Ratio with the “fractional position” $\chi_\eta$ for cluster of size two.

$$\frac{dN}{d\eta}, \quad \eta \equiv \frac{Q_{Right}}{Q_{Left} + Q_{Right}}$$

$$x(\eta) = \frac{1}{N_0} \int_0^\eta \frac{dN}{d\eta} d\eta$$

**Standard Strip sensor**
- Uniform SNR ratio over the strip width

**Artifact (selection algorithm, Cluster size two close to the edges)**

![SNR vs. fractional position graph](image)
Gain Spatial Uniformity: Gain vs. Hit position (2)

LGAD Strip

Artifact due to front-end saturation

100 Volt bias

400 Volt bias

<i-LGAD Strip

<SNR> \sim 30

<SNR> \sim 43
Tracking performance: Reference strip sensor

- Challenges:
  - Difficult synchronization between Alibaba daq (x3) and Eudaq.
  - Saturation of the Alibaba ADC.
Tracking performance: I-LGAD strip sensor

- Hit resolution biased by saturation of the Alibava ADC?
Set-up for timing characterization and DUT

- **Time standard**: constant time interval between two picosecond IR laser pulses (1060 nm)
- **Fixed time interval**: between laser pulses generated by optical splitting and delayed recombination of a single laser pulse.
Set-up for timing characterization and DUT (2)

- Signal amplified (60db, miteq 1660) & digitized (20Gs)
- Acquired averaged waveform from I-LGAD with a time interval of 52.23 ns between pulses.
Parameter extraction of the waveform.

- Single-shot (non-averaged) superposition of signals
- For each shot measured: Rise time, Signal amplitude and noise.
- **Signal estimation** as the charge under the transient waveform
- **Noise estimation** as the RMS of charge (from the first 20ns of the waveform)

\[ \sigma \equiv \text{RMS (Charge baseline)} \]

\[ \text{SNR} \equiv \frac{\text{Signal Charge}}{\sigma} \]

Range for computing the pulse charge

Waveform section from where the baseline noise is estimated
I-LGAD Timing error estimation

- For each Bias voltage five thousand waveform acquired.
- The timing error $\sigma_{\Delta t}$ estimated from the width (sigma) of the distribution of the measured time intervals ($\Delta t$)
- Assuming timing errors similar for both pulses then $\sigma_t$ for I-LGAD is given by $\sigma_{\Delta t} / \sqrt{2}$ (quadratic sum of errors)

<table>
<thead>
<tr>
<th>Vbias [V]</th>
<th>Rise Time 1 [ps]</th>
<th>Rise Time 2 [ps]</th>
<th>Vp1 [V]</th>
<th>Vp2 [V]</th>
<th>$\sigma_{\text{baseline}}$ [au]</th>
<th>SNR1</th>
<th>SNR2</th>
<th>Charge 1 [u. a.]</th>
<th>Charge 2 [u. a.]</th>
<th>$\Delta t$ [ns]</th>
<th>$\sigma_t/\sqrt{2}$ [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>334</td>
<td>357</td>
<td>1.105</td>
<td>1.034</td>
<td>13.5</td>
<td>20.6</td>
<td>19.41</td>
<td>279.0</td>
<td>262.0</td>
<td>52.23</td>
<td>25.45</td>
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<tr>
<td>600</td>
<td>326</td>
<td>327</td>
<td>0.965</td>
<td>0.905</td>
<td>14.8</td>
<td>17.02</td>
<td>15.99</td>
<td>252.0</td>
<td>236.6</td>
<td>52.23</td>
<td>26.87</td>
</tr>
<tr>
<td>500</td>
<td>330</td>
<td>327</td>
<td>0.815</td>
<td>0.762</td>
<td>14.8</td>
<td>16.0</td>
<td>14.97</td>
<td>237.0</td>
<td>221.6</td>
<td>52.23</td>
<td>27.58</td>
</tr>
<tr>
<td>400</td>
<td>357</td>
<td>353</td>
<td>0.677</td>
<td>0.631</td>
<td>14.4</td>
<td>14.3</td>
<td>13.34</td>
<td>206.0</td>
<td>192.1</td>
<td>52.23</td>
<td>31.82</td>
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<tr>
<td>300</td>
<td>357</td>
<td>355</td>
<td>0.526</td>
<td>0.496</td>
<td>15.1</td>
<td>11.5</td>
<td>10.77</td>
<td>174.8</td>
<td>162.6</td>
<td>52.23</td>
<td>37.48</td>
</tr>
<tr>
<td>200</td>
<td>354</td>
<td>358</td>
<td>0.370</td>
<td>0.347</td>
<td>14.6</td>
<td>9.5</td>
<td>8.63</td>
<td>139.0</td>
<td>126.0</td>
<td>52.23</td>
<td>46.67</td>
</tr>
</tbody>
</table>
Expected time error dependence with SNR

\[ \sigma_t \propto \frac{\text{rise time}}{\text{SNR}} \]

Defining the effective SNR as

\[ SNR_{\text{eff}} \equiv \frac{SNR_1 SNR_2}{\sqrt{SNR_1^2 + SNR_2^2}} \]

\[ \sigma_{\Delta t}^2 = \sigma_{t1}^2 + \sigma_{t2}^2 \Rightarrow \sigma_{\Delta t} \propto \frac{1}{SNR_{\text{eff}}} \]

47 ps @ SNR \( \approx 10 \)

25 ps @ SNR \( \approx 20 \)
Summary and Outlook

– Precise time stamping a must for future detectors to cope with very high pileup and track occupancy conditions.

– Several technological implementations under development.

– A p-in-p Low Gain Avalanche Detector (I-LGAD) to provide both high precision tracking and timing.

– As today, radiation tolerance remains the limiting issue.
THANK YOU FOR YOUR ATTENTION
... a particular case concerning radiation tolerance.

- The layout of the proposed LHC timing detectors: a mosaic of mini-pads (elements with area of few mm$^2$)
- A pad-like LGAD is also a pad-like I-LGAD therefore they exhibit the same radiation tolerance