HL-LHC upgrade program has renewed interest in Charged Particle timing at << 100 picosecond resolution. Usually with internal gain.

Acquiring high quality waveforms has been key in PICOSEC sensor development -> >>10^6 events from MPGD, Silicon, MCP over 4 years

In this talk I will describe methodology and illustrate benefits of this approach

* see “Experimental Challenges of the European Strategy for Particle Physics”, SNW
10 Years of waveform analysis from 40 MSa/s to 40 GSa/s

~2010 ATLAS ZDC waveforms reconstructed from PPM samples
-> sub-100 picosec resolution
http://library.wolfram.com/infocenter/Articles/7716/

Aug. 2018 PICOSEC Test Beam
MCP* ref. time, HyperFastSilicon
\[ \sigma_t^{\text{MCP}} \approx 4 \text{ picosec}, \sigma_t^{\text{HFS}} \approx 20 \text{ picosec} \]
LRS "Wavemaster"

interpolation of digitized waveform

\[
\frac{\sin[x]}{x}
\]

\[
\text{shannon}[t] = \sum_{i=1}^{\text{slicen}} \text{slice}[i] \times \text{Sinc}[\pi \times (t - \text{time}(i))/25]
\]
July/Aug 2017 PICOSEC data

4x 6micron HPK MCP 's +3mm Quartz
(measure ~4 picosec)

HyperFastSilicon (HFS)
(mesh readout DD-AD)
64 mm²/pixel
(measure <20 picosec)

MMegas-based “PICOSEC”
80 mm² pixel
(measure <25 picosec)

10 pad “PICOSEC”
Si- Gallium doped

RMS=19 picosec

vacuum

Ne/C2H6/CF4

\[
\frac{5.7}{\sqrt{2}} = 4
\]
2 Fast Timing Projects based at CERN (we share resources, beam, ++)

**PICOSEC: RD51 common Fund proposal in 2014 by SNW and I. Giomataris**


**new paper this week:**

Nuclear Instruments and Methods in Physics Research
Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 903, 21 September 2018, Pages 317-325

**HFSilicon: “Sensors with Internal Gain”-started in 2015**

M. Centis Vignali, M. Gallinaro, B. Harrop, C. Lu, M. McClish, K. T. McDonald, M. Moll, F. M. Newcomer, S. Otero Ugobono, and S. White

**subset originated in 2011 DOE AD R&D award to:**
Growing, highly motivated group w. serious commitment to Instrumentation
Outline

1) Development of PICOSEC MPGD based detector (24 picosec)
   - Cerenkov Radiator, similarities to MCP
   - Drift Region-dominant role of diffusion and Gain

2) Application of similar modeling tools (SILVACO) for Silicon (20 picosec)
   - SILVACO tct-edge scan tool- with Ranjeet Dalal, Delhi
   - realistic Landau/Vavilov- thin samples- with Su Dong, Stanford

3) tools for FEE development
   - CIVIDEC development - w E.Griesmayer, Vienna
   - Transimpedance amp - w. M. Newcomer(+E.Morales), U. Penn
   - quad fast ASIC (SiGe) - " " " -(w. US/CMS support)

4) Strategies for digitization
   - CMS Barrel Timing Layer prototype data (LYSO/SiPM)
   - other applications
It Takes Time

detection/multiplication in Gas detectors (1910) in Silicon detectors (1972)

The distribution of gains in uniformly multiplying avalanche photodiodes: Theory
R.J. McIntyre
IEEE Transactions on Electron Devices
Year: 1972, Volume: 19, Issue: 6
Pages: 703 - 713
Cited by: Papers (271) | Patents (9)
IEEE Journals & Magazines

Factors affecting the ultimate capabilities of high speed avalanche photodiodes and a review of the state-of-the-art
R.J. McIntyre
1973 International Electron Devices Meeting
Year: 1973
Pages: 213 - 216
Cited by: Papers (12)
IEEE Conferences

Theory and practice of Si w. internal gain relatively new.
1) most common, “reachthrough” diodes (aka “lgad”) ~1970’s, MIP timing in ’90’s
2) higher gain, “deep depleted” (our focus) started in ’90’s
   cooperative R&D w Gas(RD51) benefitted less mature Si modeling
ATLAS/CMS timing upgrades all based on Si w gain
-> justifies continued development of underpinnings

interesting, possibly deep, phenomena not yet traceable to particular gain model

waveform data may reveal features not anticipated in models
-> Si structure modification to mitigate degradation (~x2) due to Landau?
-> """" " " degradation due to radiation damage? .......

this worked w. PICOSEC (see below) -> then traced to simulation tools

In any case waveform data key in guiding FEE and digitizer strategy.
Ionization or Photodetection?

PICOSEC detector concept

Note similarity to MCP (next)

Mesh readout deep-depleted AD aka “HyperFast Silicon”

developed discrete TIA in Si/Ge -> quad ASIC
detailed understanding of MCP applies to -> PICOSEC

see L. Sohl 2018 Elba

Cerenkov in HPK MCP window (note similar to MMegas 3mm )

in multi-pad PICOSEC combine pads to restore “full signal”
as with MCP, PICOSEC(next) timing with full Cerenkov cone

Track Impact for hits above noise in MCP, Peak Amplitude vs. Impact and Peak Distribution for RMCP < 4.5 mm

unlike PICOSEC, MCP response to photoelectrons simple!

-> tools (in collaboration w Wolfram Research) to do complete analysis in cloud

see. M. Guth talk at DIANA-HEP Oct. 30, 2017

<-drop binary scope file in cloud app

it sends you back report
very good data quality from HFS in 2017!

why initiate something in MPGD?

- big enthusiasm in GDD/RD51 because speed ensures continued relevance
- potential benefit of continuous MIP signature (ie no Landau)
- a hedge against rad hardness of Silicon w Internal Gain
- “this seems like the right way to get inexpensive, large area timing”-R. Horisberger

Original single-pixel PICOSEC prototype

Main elements:
- Bulk MM readout.
- 3 kapton rings spacers to define the drift.
- A crystal + photocathode.
Ongoing Program of laser (for single photoelectron response) and H4 (150 GeV Muon beam)

Laser

![Diagram of Laser Setup]

- Femtosecond Ti:S laser $\lambda = 740$ nm, 120 fs, 76 MHz
- Optical Parametric Oscillator $\lambda = 560$ nm, 120 fs, 76 MHz
- Second Harmonic Generator, $\lambda = 280$ nm
- Pulse-Picker 11-300 kHz
- MicroMegas
- LeCroy 9000 digital oscilloscope
- Attenuator and bandpass filters

Typical single pe signal w. 40 dB CIVIDEC

- $t_{\text{rise}} \sim 100$ ps

we measure signal time-of-arrival from leading edge of fast electron part using "local CF", Leading edge fit, and full pulse modeling ie corrected for electronic slewing

Gas choice: optimize $\sigma_L$ and $v_{\text{Drift}}$ but favor stability

- several CF4+ quencher
- Ne/Ethane/CF4 mostly showing 90:10:10

Expectation that Preamp Gain in drift -> mitigate $\sigma_L$

See following
Key to MIP performance is:
- time-of-arrival and jitter vs. single pe signal

“Compass Gas” = Ne/Ethane/CF4 90:10:10

above dT “time-walk” corrected
- residual shift from physics of Gain

whole waveform shifts
- slices of Gain (by factor 4)
Summary of selected Single pe and MIP timing PICOSEC
(July, Aug, Oct 2017)

consistency between
<---single pe
and
150 GeV Muon results
<N_{pe} >~10

many similarities between PICOSEC and HFS
mutually beneficial

H4 Testbeam resolution(PICOSEC)
HyperFast Silicon: low cost laser, 1 MeV e-source, 140 MeV muon beam

- Instapulser
- 980 nm Vcsel
- MCP test
- Penn1 w fiber input
- Vcsel driver and HFS output traces
What is best time jitter for 1MIP equiv?

- Eric Delagnes and I tried this w. earlier FEE and SAMPIC see:
  
  **D. Breton: Elba 2015**
  
  [https://agenda.infn.it/getFile.py/access?contribId=138&sessionId=11&resId=0&materialId=slides&confId=8397](https://agenda.infn.it/getFile.py/access?contribId=138&sessionId=11&resId=0&materialId=slides&confId=8397)

  here we look at data from lab using Mitch’s amp

---

**Laser and HFS signal, 1 MIP equivalent, ~20 deg. C**

- Unfiltered baseline noise ≈ 2.2mV rms
- $\text{SNR} \approx \frac{400}{2.2} = 180$
- Risetime = 0.65ns

Naively jitter from noise:
$$dt \approx \frac{t_R}{\text{SNR}} = 3.6 \text{ picosec}$$
timing algorithm

• since there is some spread in laser amplitude we typically do simple Constant Fraction timing on the leading edge at ~20%. Other techniques such as filtering (usually Wiener) and fit, signal modeling, etc. all give equiv results for this example.

• here we do a simple power law fit to the full waveform.

transposed leading edge

nice result but contribution from trigger jitter? no

rms=8.9 picosec
alternative to local Constant fraction fit is signal modeling for which Mathematica has some nice tools

Map function across waves

Here I use MapIndexed (this allows me to use the position as an argument). Dataset groups the results together.

\[
\text{ds} = \text{Dataset}[	ext{MapIndexed}[	ext{fit}[\#1, \#2[[1]]] \&, \text{wave4}[[1 ;; 100]]]]
\]

<table>
<thead>
<tr>
<th>event</th>
<th>bestFitParameters</th>
<th>adjustedRSquared</th>
<th>plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{A \rightarrow 0.119864, n \rightarrow 2.11306, to \rightarrow 0.592996, toff \rightarrow 6.41963}</td>
<td>0.994857</td>
<td><img src="image1" alt="event 1" /></td>
</tr>
<tr>
<td>2</td>
<td>{A \rightarrow 0.0962981, n \rightarrow 3.7208, to \rightarrow 0.401652, toff \rightarrow 11.3142}</td>
<td>0.992228</td>
<td><img src="image2" alt="event 2" /></td>
</tr>
<tr>
<td>3</td>
<td>{A \rightarrow 0.11766, n \rightarrow 3.70992, to \rightarrow 0.454327, toff \rightarrow 4.29665}</td>
<td>0.994448</td>
<td><img src="image3" alt="event 3" /></td>
</tr>
<tr>
<td>4</td>
<td>NonlinearModelFit::sszero</td>
<td>-</td>
<td><img src="image4" alt="event 4" /></td>
</tr>
<tr>
<td>5</td>
<td>{A \rightarrow 0.0926168, n \rightarrow 2.05265, to \rightarrow 0.595536, toff \rightarrow 7.40185}</td>
<td>0.991077</td>
<td><img src="image5" alt="event 5" /></td>
</tr>
<tr>
<td>6</td>
<td>{A \rightarrow 0.11257, n \rightarrow 2.50197, to \rightarrow 0.506459, toff \rightarrow 17.7226}</td>
<td>0.9939</td>
<td><img src="image6" alt="event 6" /></td>
</tr>
<tr>
<td>7</td>
<td>{A \rightarrow 0.0667517, n \rightarrow 4.39367, to \rightarrow 0.377799, toff \rightarrow 27.448}</td>
<td>0.986334</td>
<td><img src="image7" alt="event 7" /></td>
</tr>
</tbody>
</table>
an alternative to HE beam

small device (~6”)
~1 Amp drive current
selects to +/-10% 1 MeV electrons
Argonne made similar in SSC era, fell into disuse
Some test beam results from 2016-17

early result showing promise of HFS

2016: Nice Amplitude Uniformity over 64 mm$^2$ pixel

similar time res. at edge & center however 10-20 picos time walk -> attributed to packaging/interconnect
goal of 2017 to eliminate walk
SILVACO used to model radiation damage & Landau Contribution to Timing

M. Moll, RD50 mtg.
June 2016

Voltage: 1800 V
16 positions (16 slices)

Meanwhile, Packaging evolution

1 GeV muon, 5μm silicon

Histogram based on PDF

Deposited Charge [KeV/5μm silicon]

Packaging by Bert Harrop, Princeton
discrete TIA from U. Penn. (M.Newcomer)

Figure 10. A photograph of a 1st generation PCB with a mounted mesh APD seen on the right-hand side of the PCB.

Figure 11. (Left) A close up photograph showing the wire bonded APD anode. (Right) A close up photograph showing the wire bonded Ni mesh screen.
2017, 2018 (150 GeV muons) => improved speed from FEE Integration

Gain range in 2017

HFS Gain vs. HV

with improved integration and constant iterations in Penn design
see real impact on signal quality
thank you Mitch & Bert!

Mitch N’s ASIC (funded by US/CMS)
also back from MOSIS
first look in Aug ’18 beam
Discrete Fourier Transform
-useful language to correspond w FEE designers

our test beam noise spectrum
confirmed by E. Griesmayer (Cividec) - SPICE

first test beam exposure of HFSilicon w Mitch Newcomer's new ASIC Aug. 2018
Useful interaction on architecture for CMS Readout
(LIP, CERN, U. Virginia)

“end of life” $x10^5$ increase in Dark counts
a challenge for CMS baseline subtraction

-> collaborate w LIP design team using laser
and dc waveforms to validate simulations

could 2 threshold tdc replace
1 threshold + pulse area in CMS Barrel?
“yes, maybe better”-A.Ledovskoy, U.Va.

similar questions in other fields:

CMS LYSO/SiPM

A 100-ps Multi-Time over Threshold data acquisition system for cosmic ray detection
some conclusions:

- we are in an interesting domain where detector physics rather than electronics (SNR, rise time) govern resolution

- the principle technology choices of the LHC upgrades are based on Silicon with internal gain

- unlike the case with gas detectors, the fundamental timing limitations not fully modeled. -> well worth pursuing

- at the same time there is a real opportunity to use a combination of modeling and machine learning on a large data set to further develop signal processing algorithms. Subject of a current proposal with Wolfram Research.

thanks for your attention!
BACKUP
2017 beam Campaigns within PICOSEC infractructure (cont)

Signal modeling useful to probe position dependence

HyperFast Silicon Signal fitted to 4 parameter Gamma Distribution, GridLines at 20%

HFS Pulse Width vs. Track Impact in x and y

mcp
TrkGEM1: Mean ADC vs. Hit Position Map

Entries: 854
Mean x: 21.02
Mean y: -22.21
RMS x: 4.985
RMS y: 4.929

<--- small area, aligned
large area trigger --->

HFS (Penn2) – MCP time vs. x impact, y impact and Amplitude (V) – (nanosec vertical scale)

HFS Penn2 Peak vs. x -- -- -- -- -- -- -- -- and Peak vs. y and -- -- -- -- -- -- -- -- Full Landau Distribution
a tour of HFS laser

- Laser characterization was useful for developing capacitive(mesh) readout, etc.
- It provides a baseline performance, free of time jitter due to Landau/Vavilov
- Goal is to make a laser pulse that deposits same average charge profile as a MIP
- Few 10’s of micron Si pretty transparent~1000nm IR
- We use typically 980nm or 1060nm

Few 100 picosec laser drivers typically pricey so Mitch Newcomer and I developed a cheap one “Instapulser CMS”
Laser Pulse Intensity

- rather than dead-reckoning (ie calculating e-h pairs/micron and gain elements) we compare, in situ, HE beam response to a stable reference (ie Fe55 X-ray source). Also nice momentum selected 1MeV electron source.

MIP signal ~ 140 mV

peak pulse height distribution from 5.4 keV Cr X-rays ~1/3 of most probable MIP(150 GeV muons)
routinely adjust laser intensity vs. Fe55 once this equivalence established

Most probable signal for 5.9 keV X-ray (~1600 e-h pairs) easily seen for a given detector bias. 
-> set laser intensity for roughly 3\* larger signal.  
Then vary bias to set different internal gain in HFS.