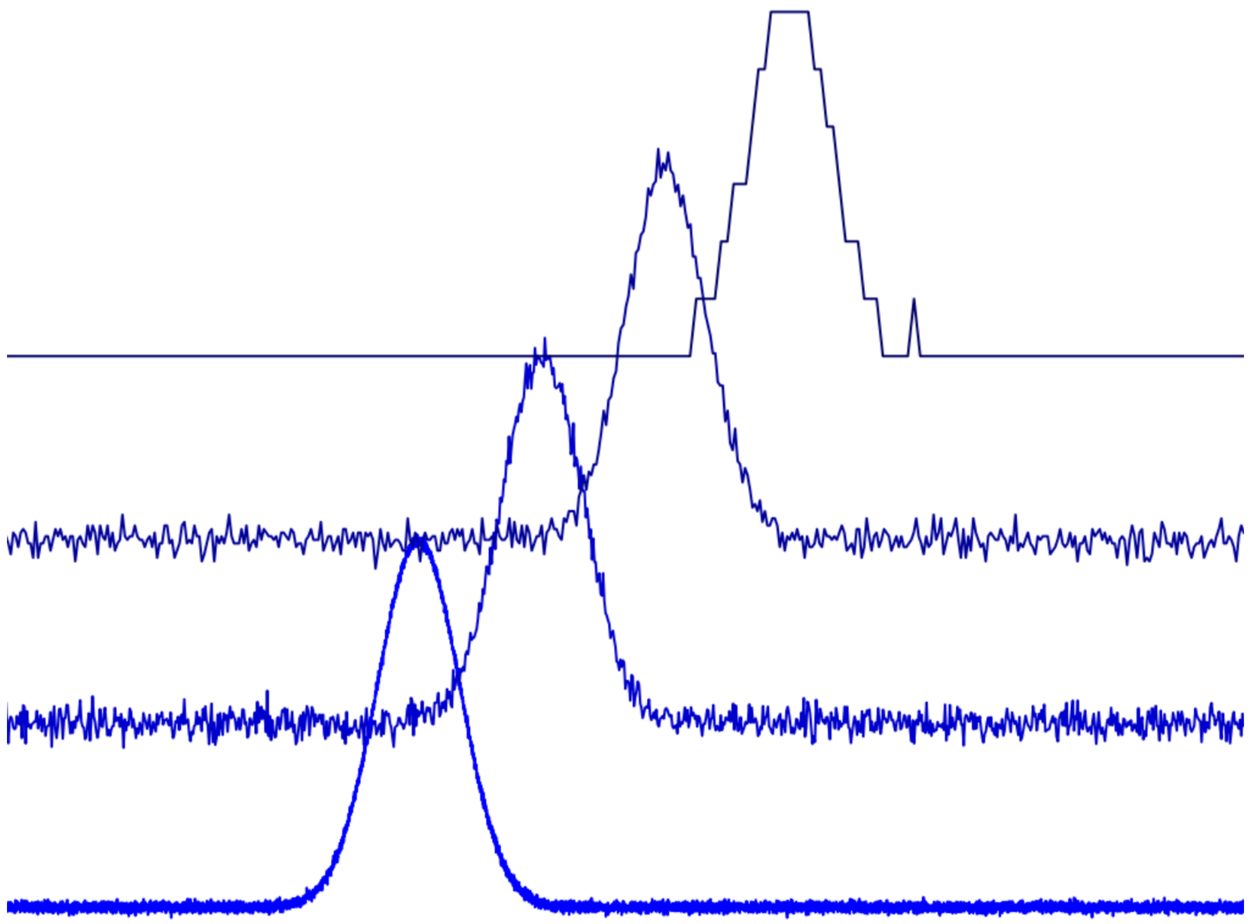
Fast Digitizers for Particle Physics



Nicola Minafra

The University of Kansas

16th June 2021

O utline

Fast Digitizer for Particle Physics	*Nicola Minafra*
remote-only by Zoom	16:10 - 16:25
Architecture of the SAMPIC digitizer	*Dominique Robert Breton*
remote-only by Zoom	16:25 - 16:40
Fast timing electronics R&D based on waveform digitization	*Jiajun Qin et al.*
remote-only by Zoom	16:40 - 16:55

Digitization of the signal:

- why?
- how?
  - a bit of theory (only a bit!)
  - digitization using fast ADC
  - digitization using a Switched Capacitor Array

Particle Physics examples:

- SAMPIC for the CMS PPS timing detector
- PSEC4 for PID in a cube sat
- Digital scope for beam profile characterization

Digitization of the signal.... W h y ?

A sampled signal contains all the information needed for a precise measurement and to debug the system

Advantages of sampling:

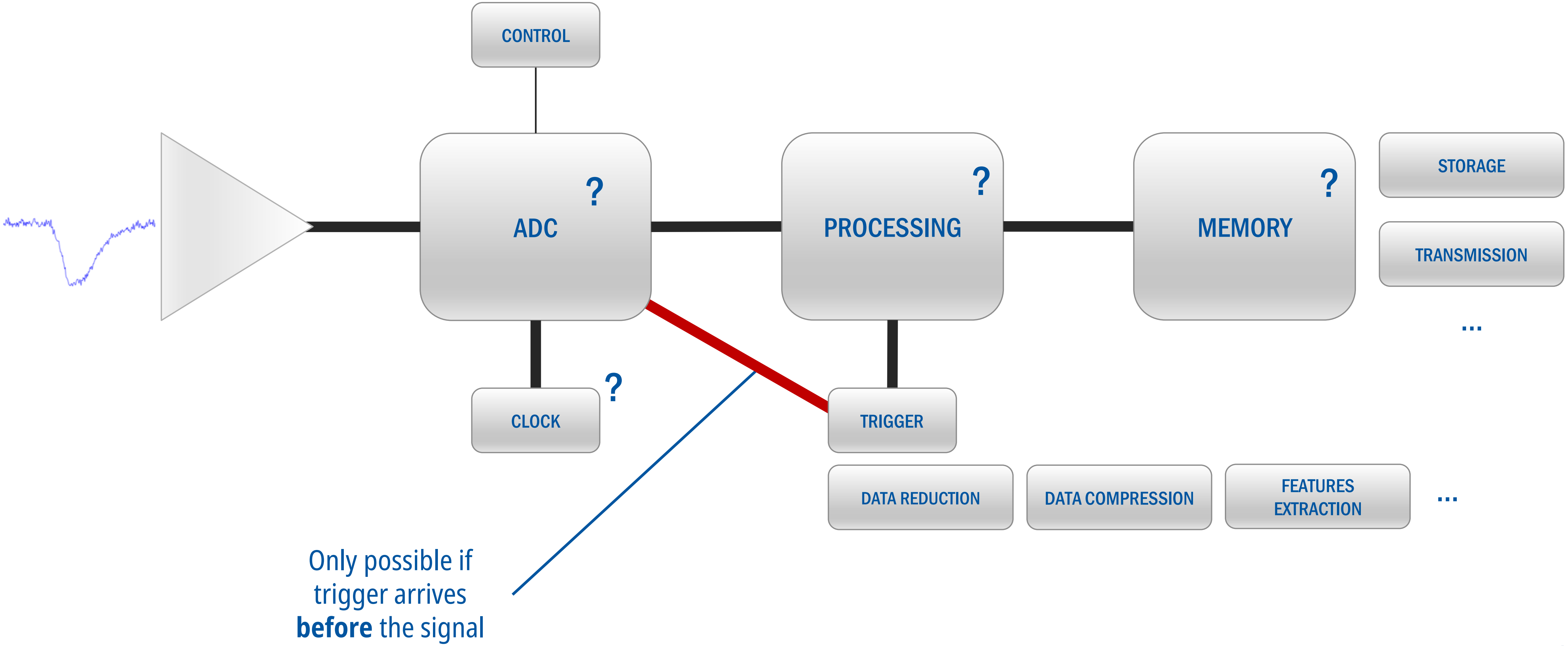
- *Infinite* analysis possibilities
- Possible to improve performance off-line
- Digital elaboration (Moore's law)

Cons

- High cost
- Requires computing power
- Usually slow and bulky devices

Digitization of the signal…. H o w ?

The analog signal is amplified and digitized using an Analog to Digital Converter (ADC)



Digitization “without” loss of information

The system can be designed in a way the measurement is limited by the detector and not by the digitizer

1- Nyquist–Shannon sampling theorem $f_{SAMPLING} \geq 2\, f_{SIGNAL}$ (assuming sinc antialiasing)

Rule of thumb (conservative): $f_{SAMPLING} \sim 3 f_{SIGNAL}$

2- Quantization noise

$SNR\ [\text{dB}] = (6.02\ ENOB) + 1.76$

ENOB: effective number of bits

quantization error is uniformly distributed between −1/2 LSB and +1/2 LSB for a sine wave

ENOB 8 bits: SNR ~48 dB (256)

Diamond SNR ~ 28 dB (25) -> quantization is degrading the SNR by ~0.5%
LGAD SNR ~ 40 dB (100) -> quantization is degrading the SNR by ~7%

Digitization “without” loss of information

The system can be designed in a way the measurement is limited by the detector and not by the digitizer

Technical Data

Bandwidth	1 GHz
Channels	4
Memory	62.5 M - 1 G points
Samplingrate	25 GS/s - 50 GS/s (2.5 TS/s interpolated)

Sample rate	Number of bits of vertical resolution
50 GS/s	8
25 GS/s	8
12.5 GS/s	12
6.25 GS/s	13
3.125 GS/s	14
1.25 GS/s	15
≤625 MS/s	16

Effective bits (ENOB), typical

2 mV/div, High Res mode, 50 Ω, 10 MHz input with 90% full screen

Bandwidth	ENOB
5 GHz	5.7
4 GHz	5.9
3 GHz	6.1
2.5 GHz	6.2
2 GHz	6.35
1 GHz	6.8
500 MHz	7.25
350 MHz	7.5
250 MHz	7.65
200 MHz	7.85
20 MHz	9.25

resolution ≠ precision

Table 3: 50 GS/s, Sample Mode, RMS

V/div	1 mV/div	2 mV/div	5 m
10 GHz	183 μV	188 μV	228
9 GHz	167 μV	172 μV	208
8 GHz	153 μV	156 μV	192
7 GHz	139 μV	141 μV	175
6 GHz	124 μV	127 μV	156

Table 4: 25 GS/s, HiRes Mode, RMS

V/div	1 mV/div	2 mV/div	5
5 GHz	111 μV	112 μV	1
4 GHz	97.4 μV	98.7 μV	1
3 GHz	83.8 μV	85 μV	1
2.5 GHz	75.6 μV	76.6 μV	9
2 GHz	68.9 μV	69.9 μV	8
1 GHz	51.1 μV	51.8 μV	5
500 MHz	37.5 μV	38 μV	4
350 MHz	31.9 μV	32.3 μV	3
250 MHz	28.1 μV	28.5 μV	3
200 MHz	24.2 μV	24.5 μV	2
20 MHz	8.68 μV	8.8 μV	1

Why do we need 50 GS/s?!

OVERSAMPLING!

$$f_{OS} \sim 4^W f_S$$

$$ENOB_{OS} \sim ENOB_S + W$$

https://www.linktronix.ch/en/mso64b-1000

Digitization of the signal.... H o w ?

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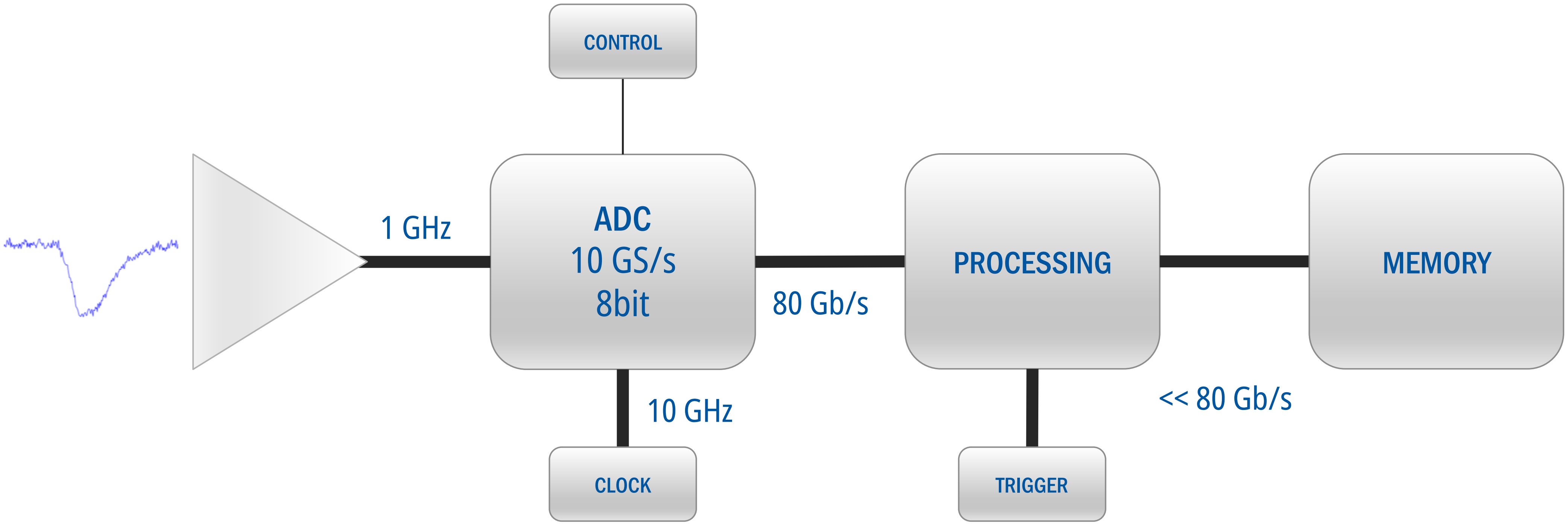


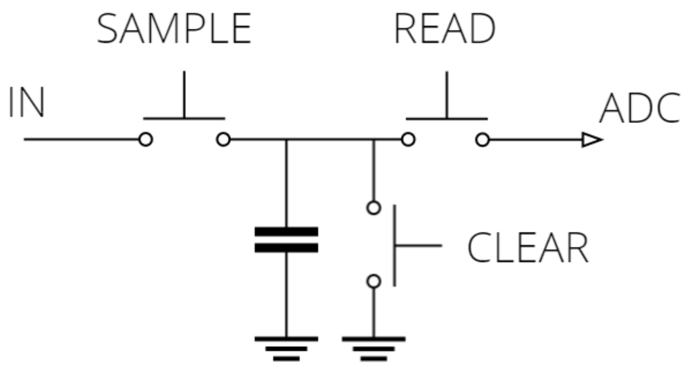
ADS54J60 2 ch 16 bit 1 GS/s 10x10 mm^2 **1.35 W/Ch**

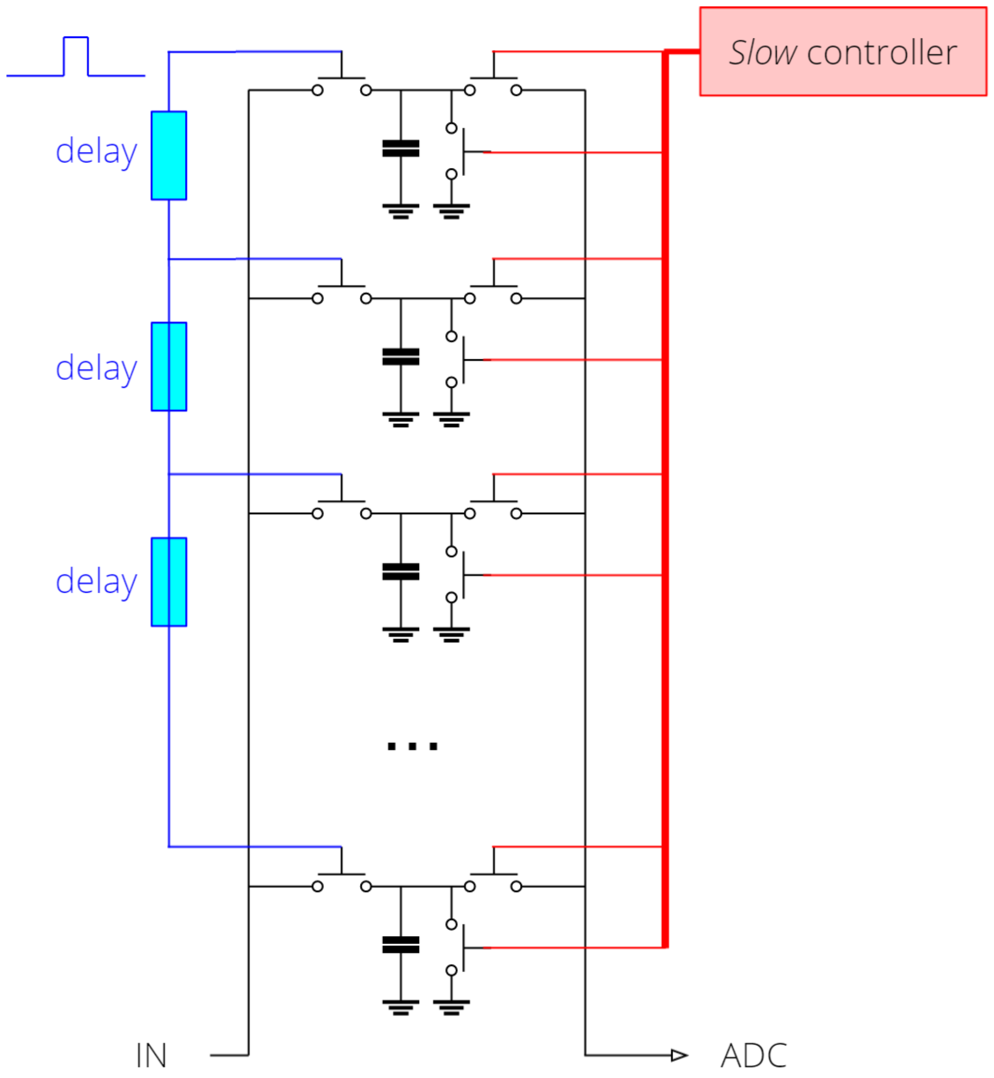
ADC12DL3200 2 ch 12 bit 3.2 GS/s (or 6.4 GS/s 1 ch) 17x17 mm^2 **3.15 W**

ADC12DJ5200RF 2 ch 12 bit 5.2 GS/s (or 10.4 GS/s 1 ch) 10x10 mm^2 **4 W**

Can we decouple sampling and digitization?

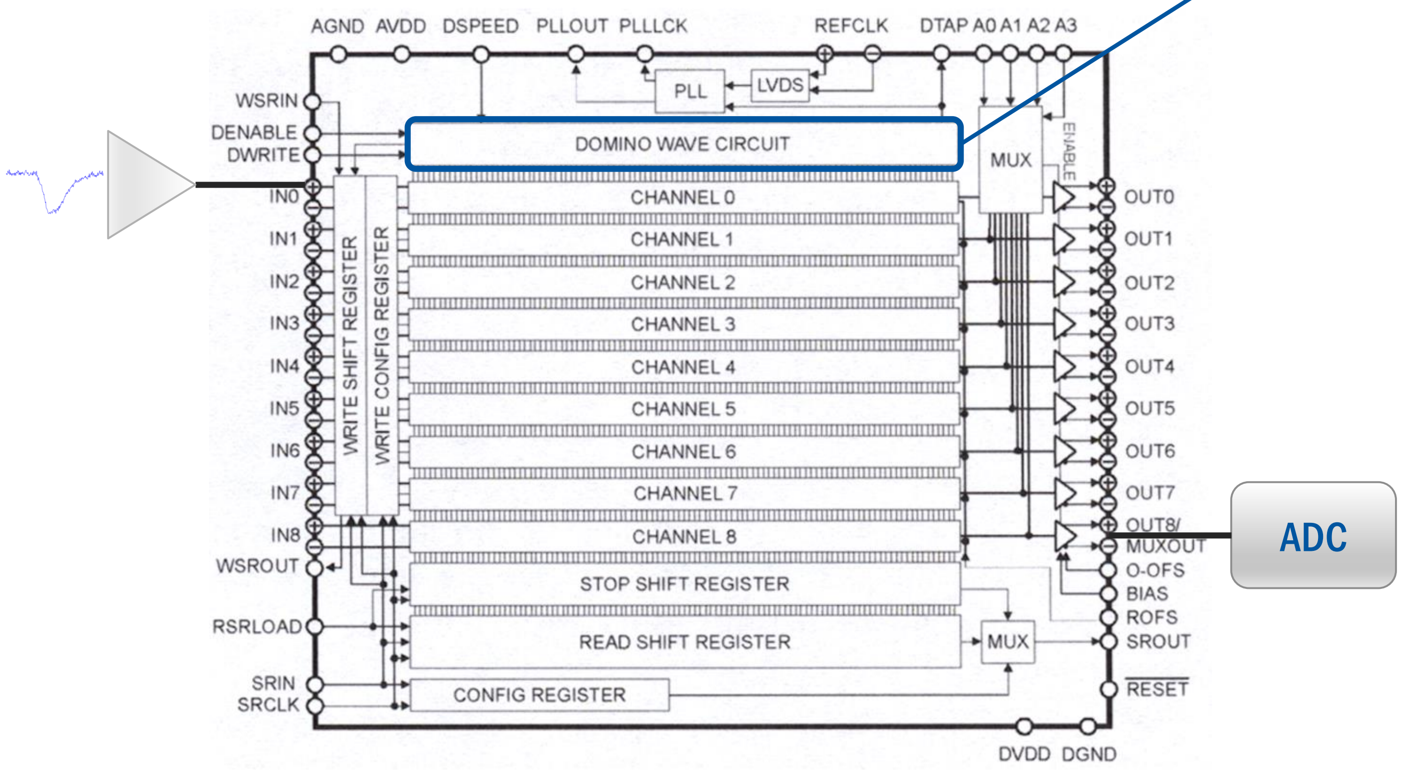
We can use a fast electronics to sample the signal and then a slower electronics to digitized the sampled signal



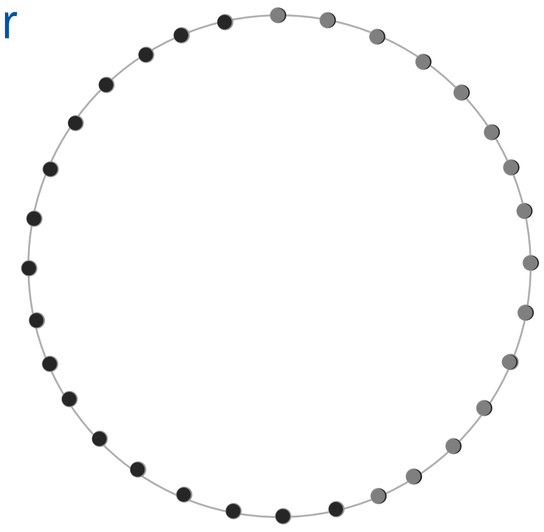


DRS4: Domino Ring Sampler

9 ch, up to 5 GS/s, 950 MHz BW, 1024 sampling cells, 140 mW



Ring buffer



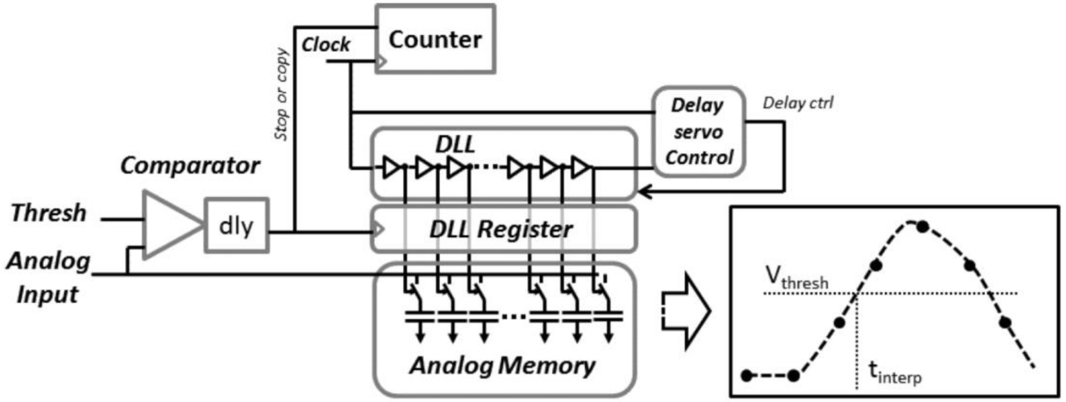
The trigger **stops** the sampling

Digitization starts (sampler is stopped)

Sampling starts again

Wavecatcher & friends...

All samples of one channel can be digitized at once: lower dead time



Wavecatcher (SAMLONG chip)

2 ch, up to 3.2 GS/s, 500 MHz BW, 12 bits, 1024 sampling cells, conversion time <66 us, 400 mW

SAMPIC see D. Breton's talk

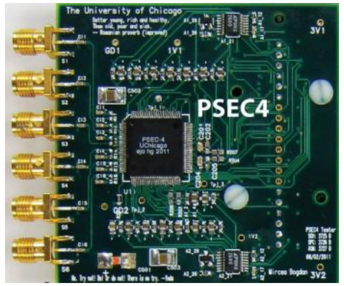
16 ch, up to 10 GS/s, >1 GHz BW, 11 bits, 64 sampling cells, conversion time 0.1 – 1.6 μs, 180 mW

PSEC4

6 ch, up to 15 GS/s, 1.5 GHz BW, 11 bits, 256 sampling cells, conversion time 4 μs, 100 mW

SCA ASIC see J. Qin's talk

8 ch, >5 GS/s, 1 GHz BW, 12 bits, 128 sampling cells, conversion time 4 μs



Outline

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Particle Physics examples:

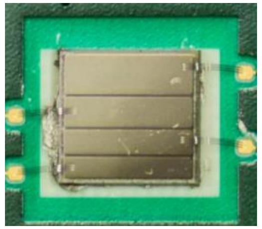
- **SAMPIC for the CMS PPS timing detector**
- **PSEC4 for PID in a cube sat**
- **Digital scope** for beam profile characterization

CMS & TOTEM Timing detectors

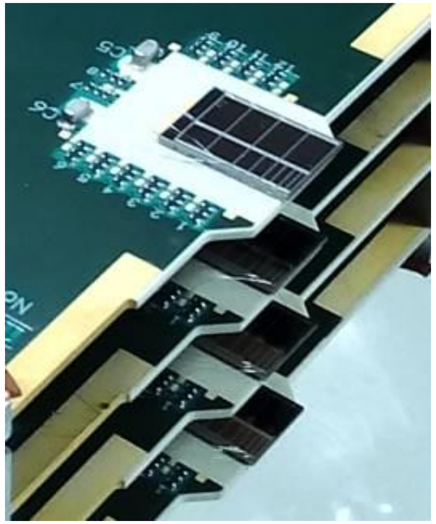
Timing detectors with <100 ps precision hosted in Roman Pots at 220m on both sides of the CMS interaction point

CMS PPS detectors:

- High radiation tolerance
- High trigger rate capabilities

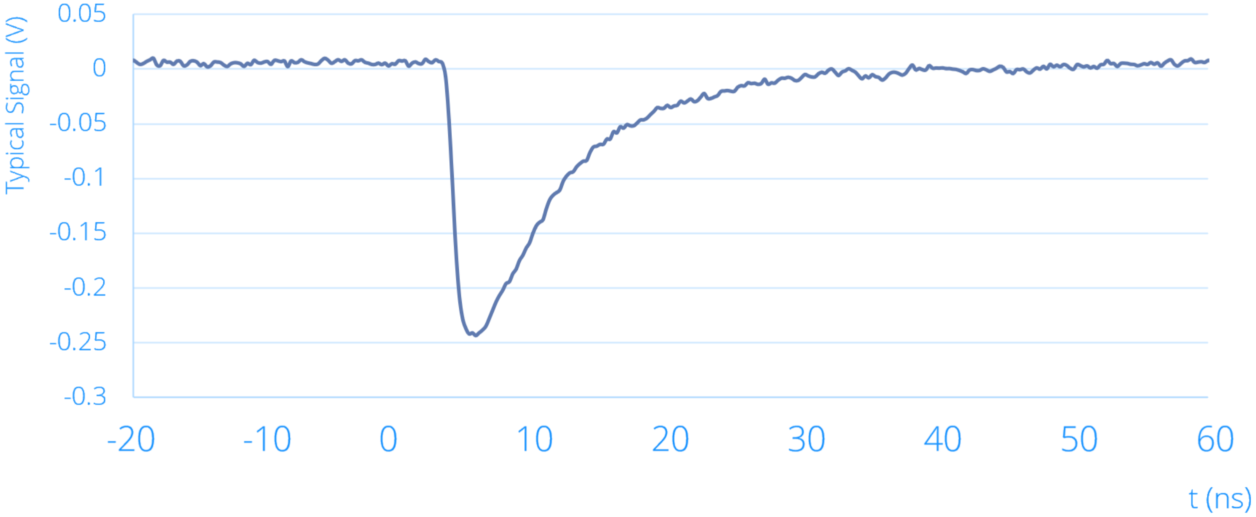


scCVD Diamond sensors, HPTDC



TOTEM detectors:

- For dedicated low luminosity runs: possibility of using LGADs and sampler



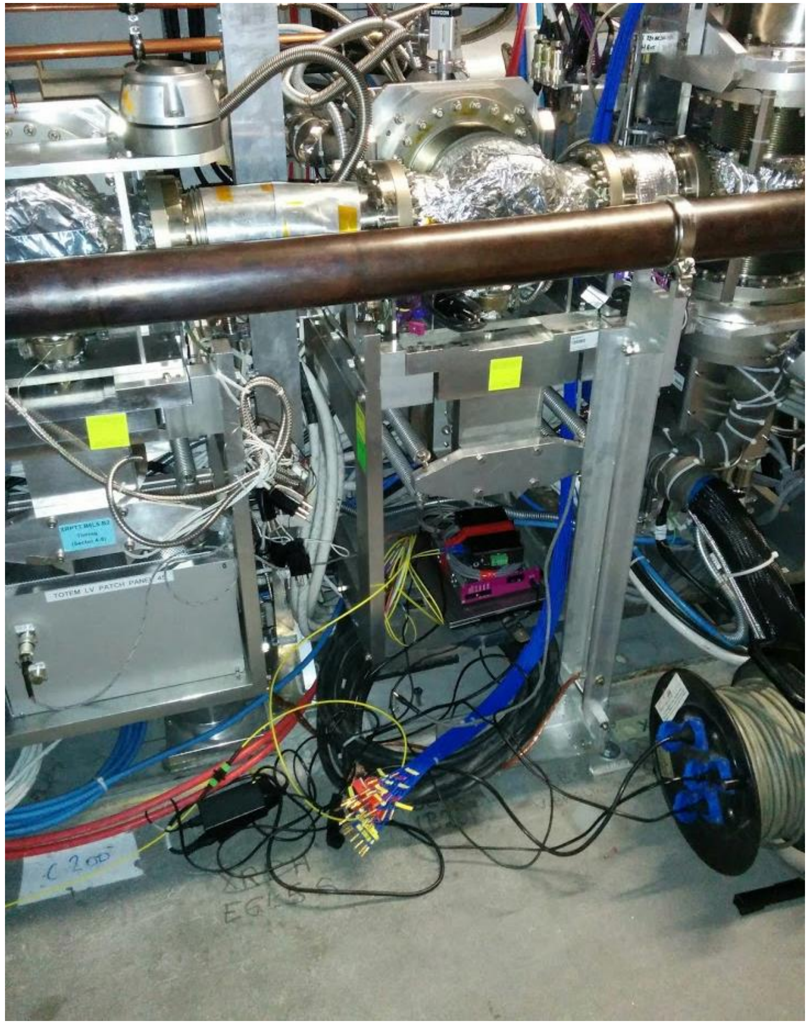
- ~1 ns rise time: >350 MHz
- ~50 SNR: >8 bits
- Interested only in the first edge: ~10 ns
- 12x4 channels
- Acceptable dead time ~ 5 us

SAMPIC!

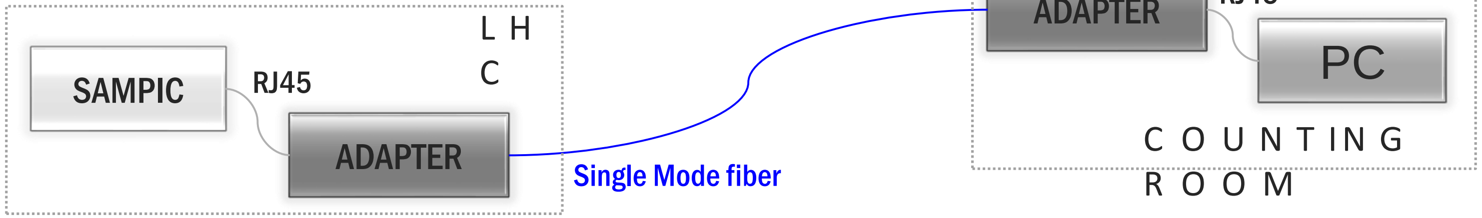
see E. Bossini's talk

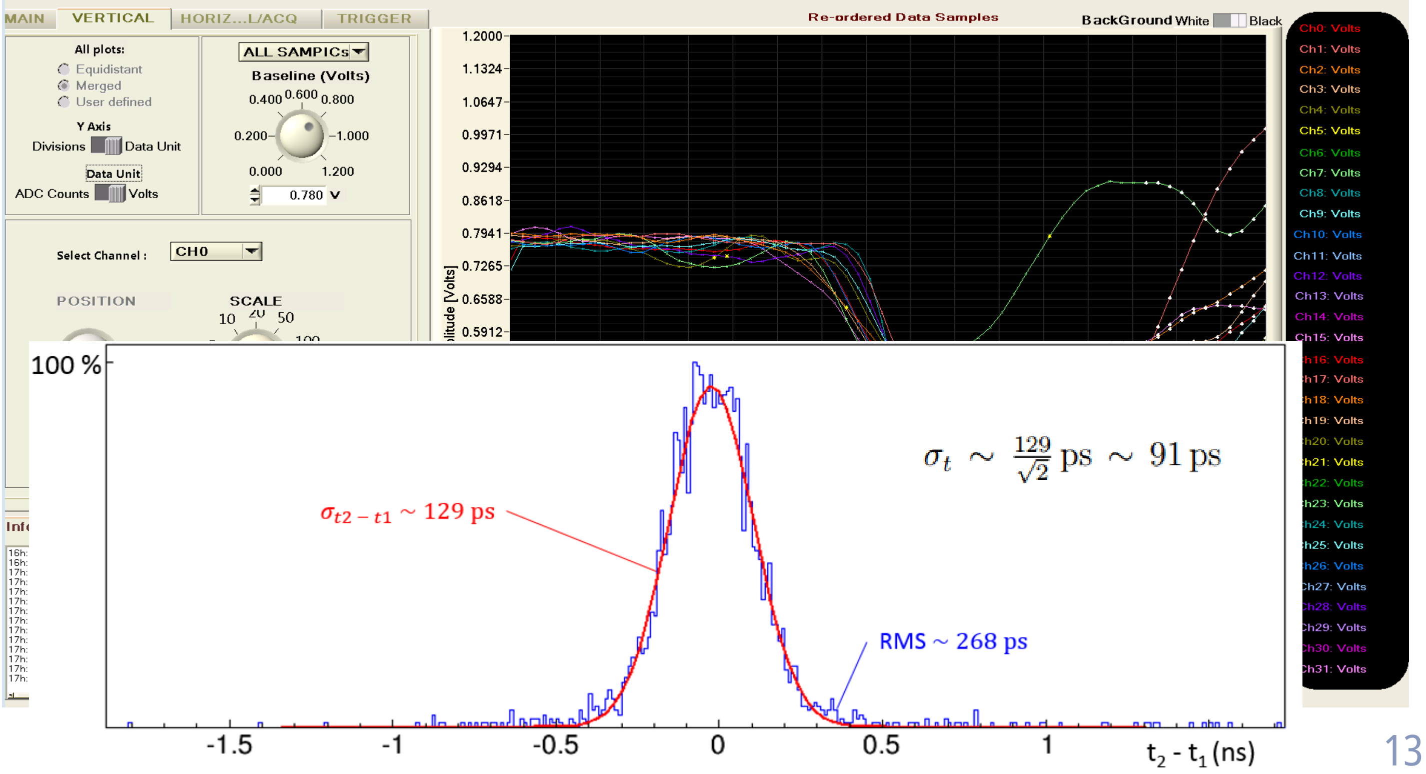
CMS PPS Timing Detectors: LHC proof of concept

A preliminary installation in the LHC proved the feasibility of a diamond timing detector with a precision of ~100 ps per plane, installed in a Roman Pot



SAMPIC was read using an Ethernet connection





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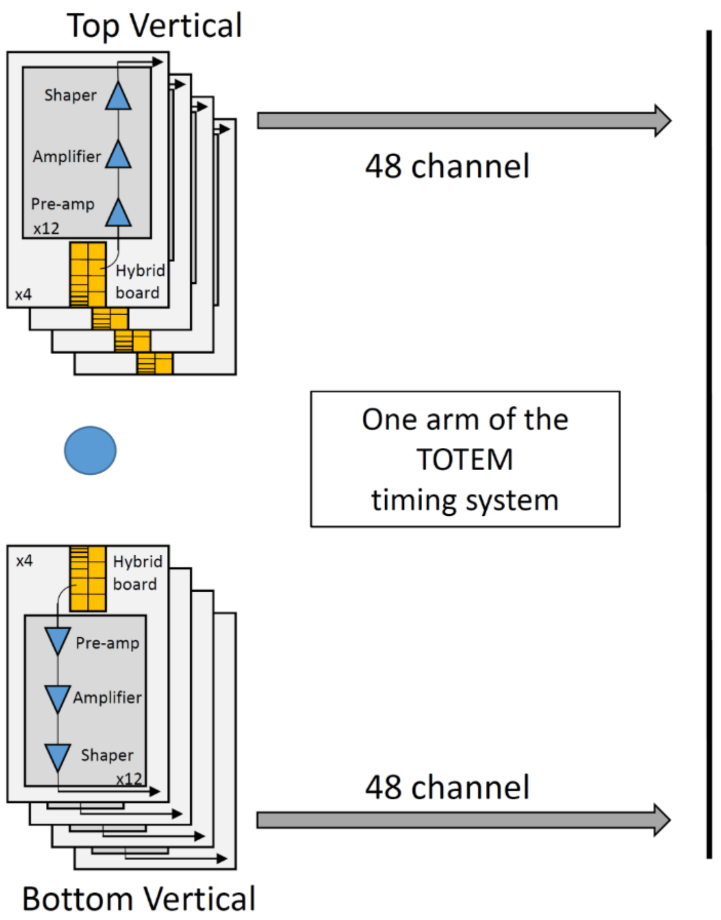
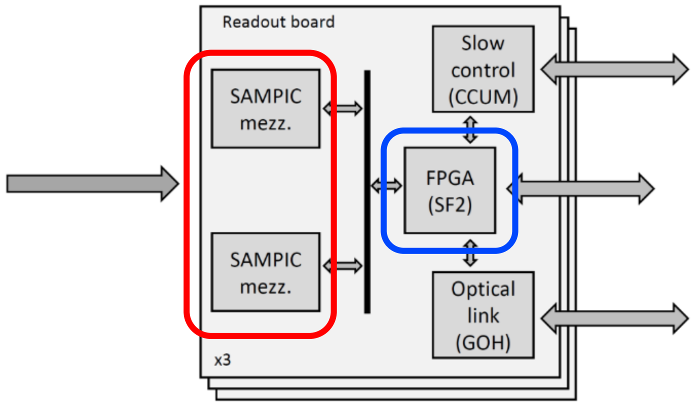
CMS-TOTEM Timing detectors

Different sensors are read-out by a trans-impedance preamplifier, then the signal can be digitized using SAMPIC or discriminated and digitized using HPTDC

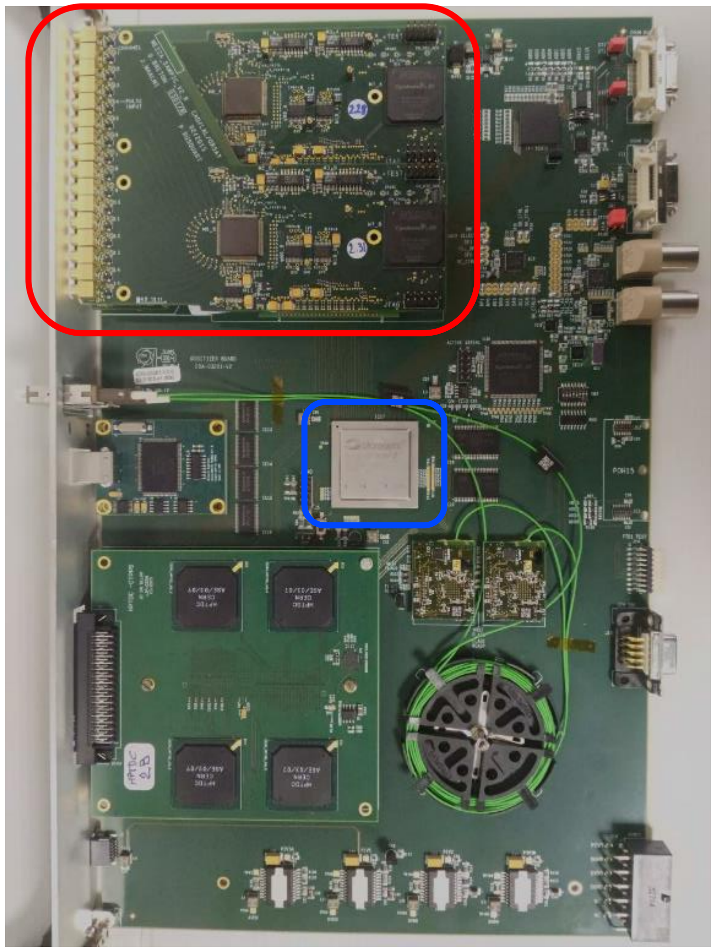




SAMPIC

- 16 channels/chip
- Up to 64 samples/hit @ 10 GSa/s
- 1.5 GHz bandwidth
- 8-11 bit resolution
- 0.2-1.6 μs channel dead time

Trigger matching and frame building done in the Digitizer Board



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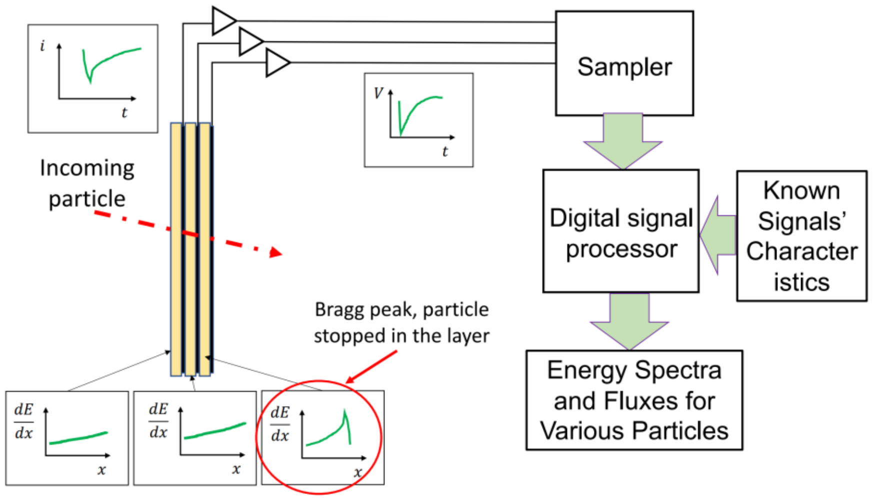
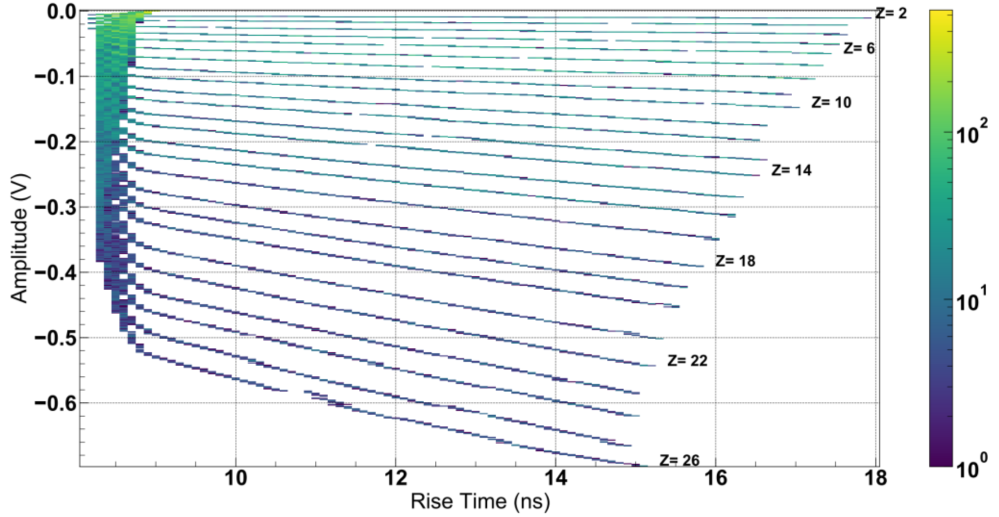
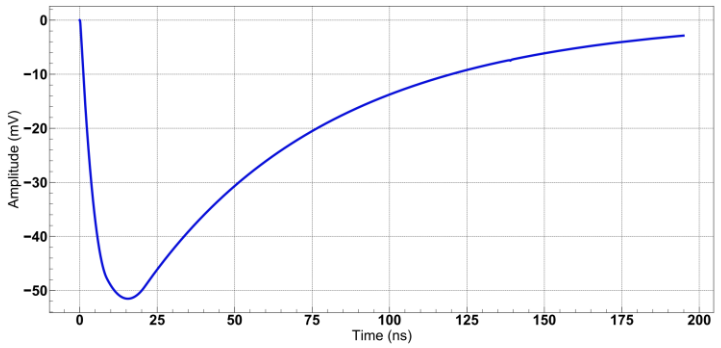
AGILE: Particle Identification with pulse shape analysis

Advanced enerGetic Ion eLectron tElescope: development of a compact low-cost instrument to detect and identify charged particles in space







- >2 ns rise time: >150 MHz
- ~10-100 SNR: >8 bits
- Interested in the full signal: >50 ns
- 3x2 channels
- Low power and small size

PSEC4!

Particle Physics on the Plains (A. Novikov)
A novel technique for real-time ion identification and energy measurement for in situ space instrumentation

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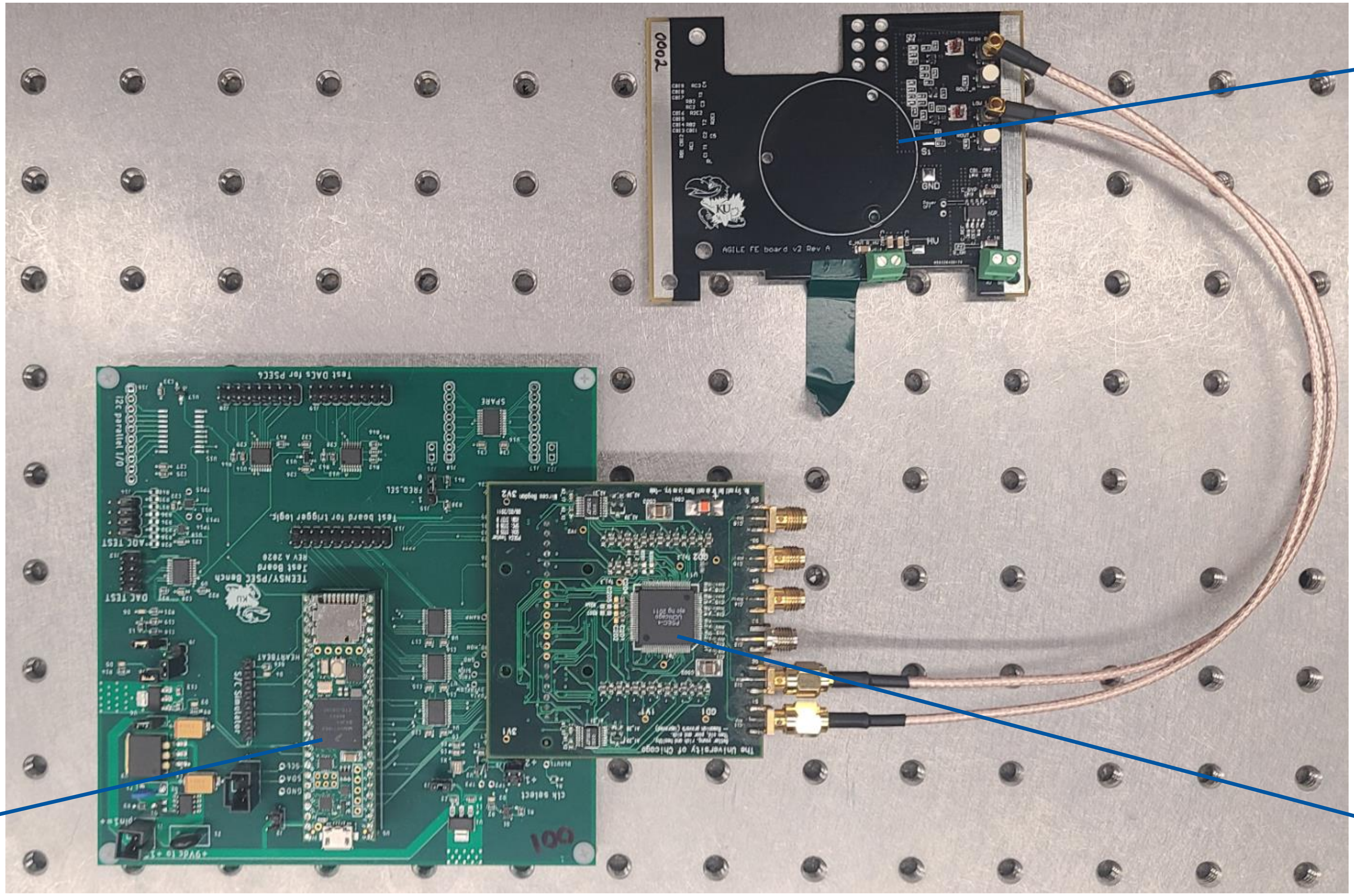


Front-end board

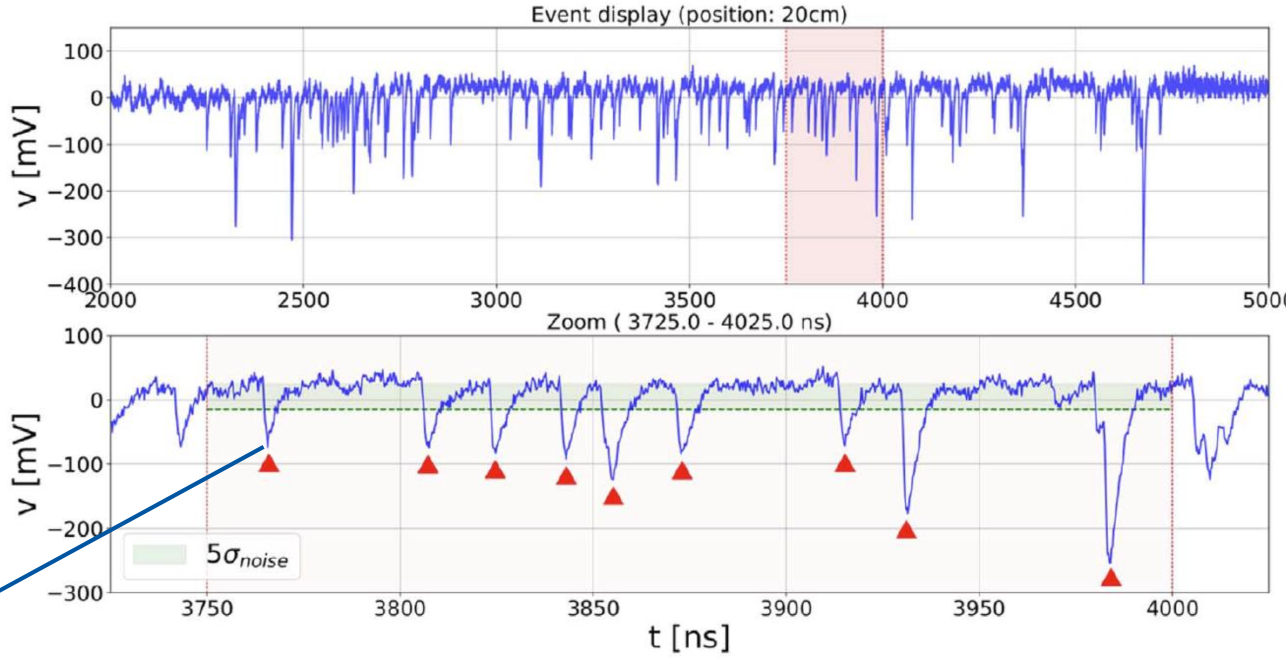
Teensy 4.1:
ARM Cortex-M7 @ 600 MHz

PSEC4 mezzanine

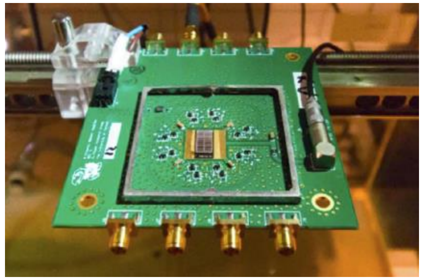
Particle Physics on the Plains (A. Novikov)
A novel technique for real-time ion identification and energy measurement for in situ space instrumentation

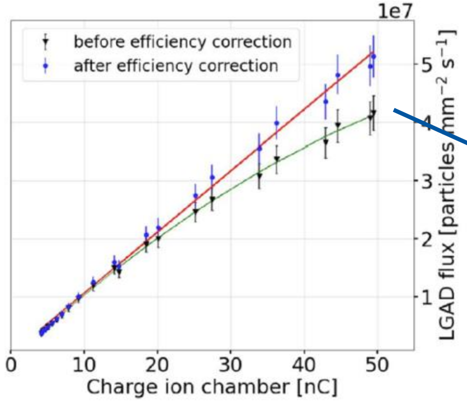
LGAD for beam profile characterization

A **digital scope** is the ideal solution to digitize a long (~5 μs) signal with high sampling rate (5 Gs/s) and with low trigger rate (~10 Hz)



Single peak identification

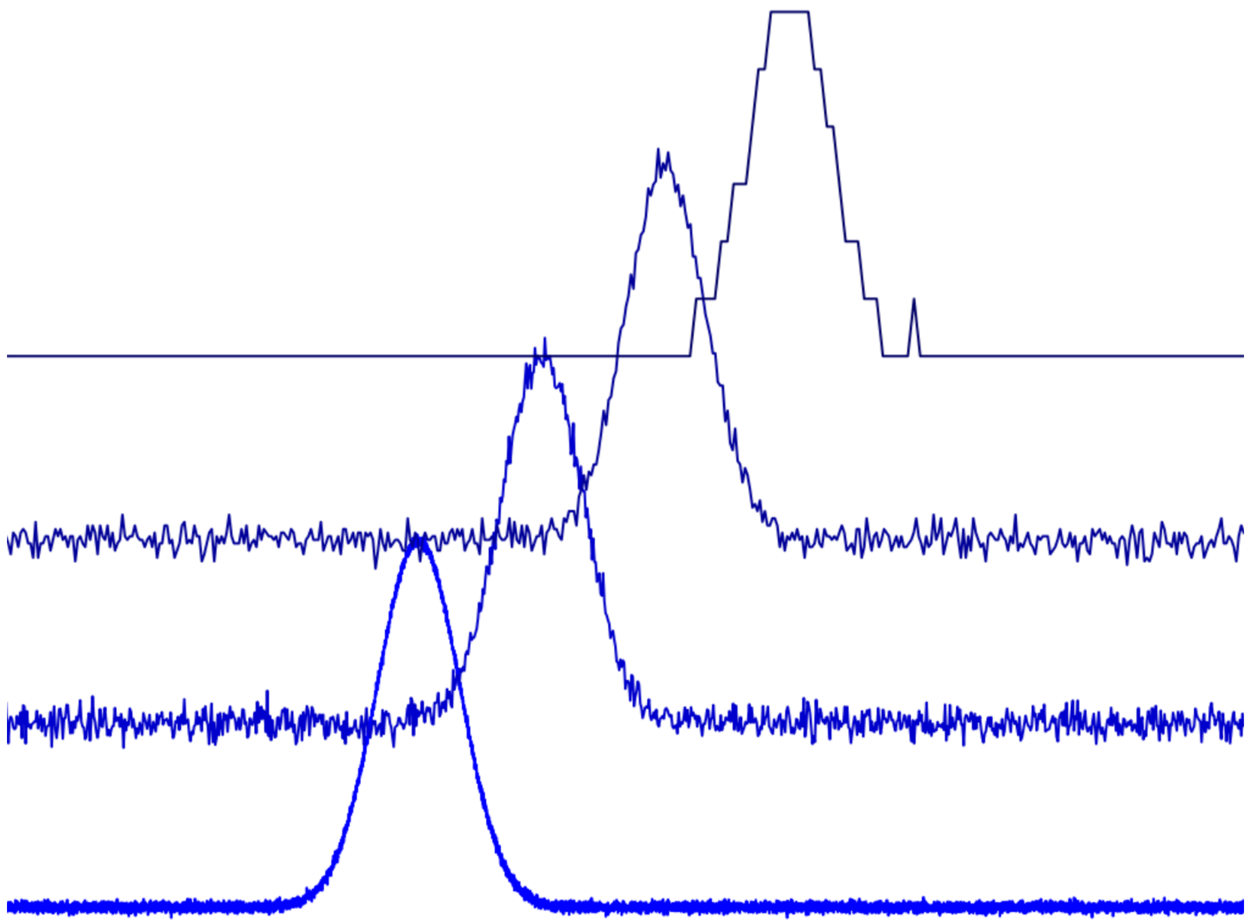




Good agreement with industry standard (ion chamber)

Particle Physics on the Plains (T. Isidori)
Performance of a low gain avalanche detector in a medical linac and characterisation of the beam profile

Fast Digitizers for Particle Physics



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