Analog Photon Processor

Workshop on
Hybrid Cherenkov/Scintillation Detection Technologies

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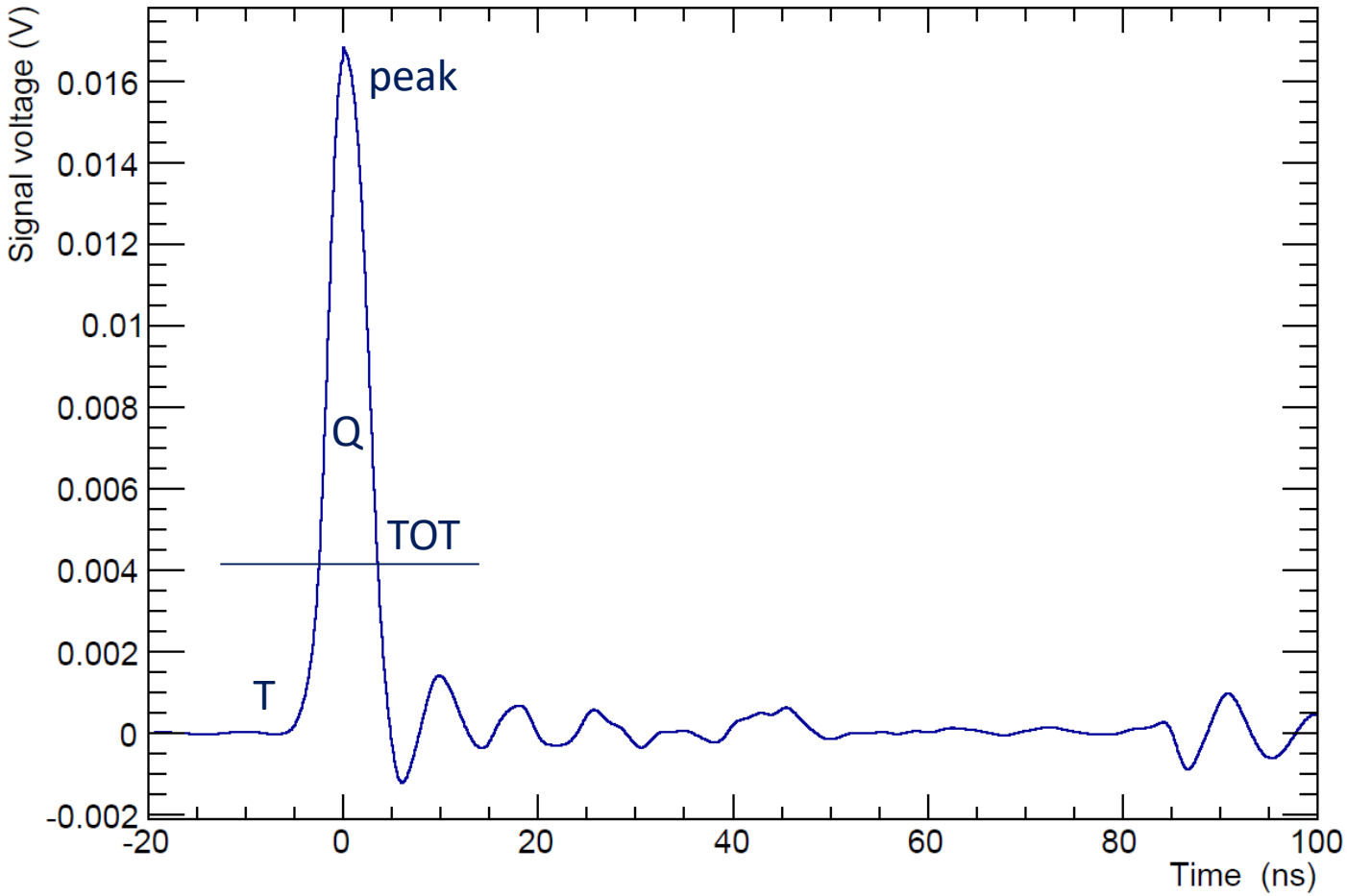
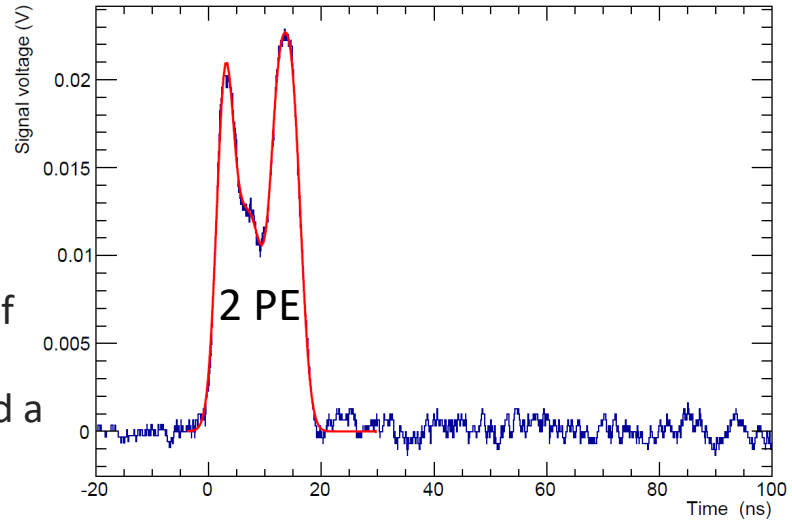
APP concept

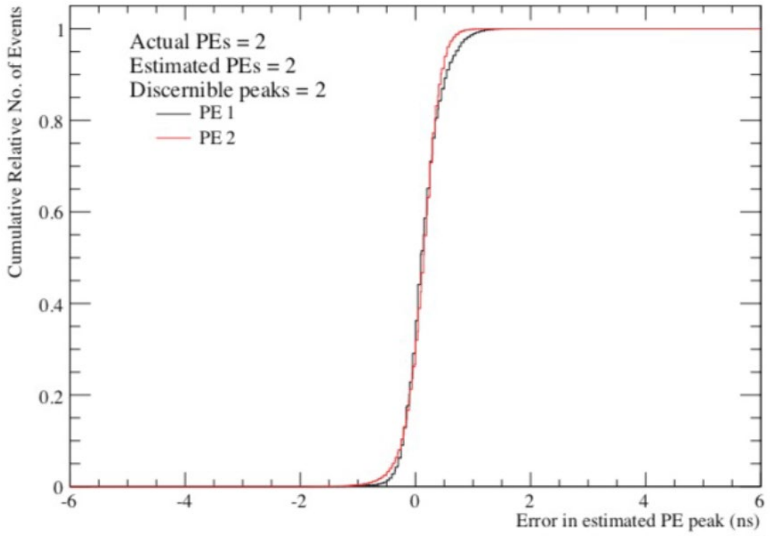
- Motivation:
  - We are interested in the number of photoelectrons (PE), and their arrival times
- Can we avoid full digitization?
  - Petabytes – exabytes per year in 10^4 channel systems
  - Power hungry
  - High cost
  - Resolution and dead time (closely spaced pulses)
- Need these parameters to characterize an arbitrary PMT pulse:
  - Leading edge time
  - Trailing edge time – get time over threshold (TOT) from edge times
  - Peak amplitude
  - Peak time
  - Total charge (Q)
- Timing resolution limited to an extent by photomultiplier tube transit time spread (TTS)

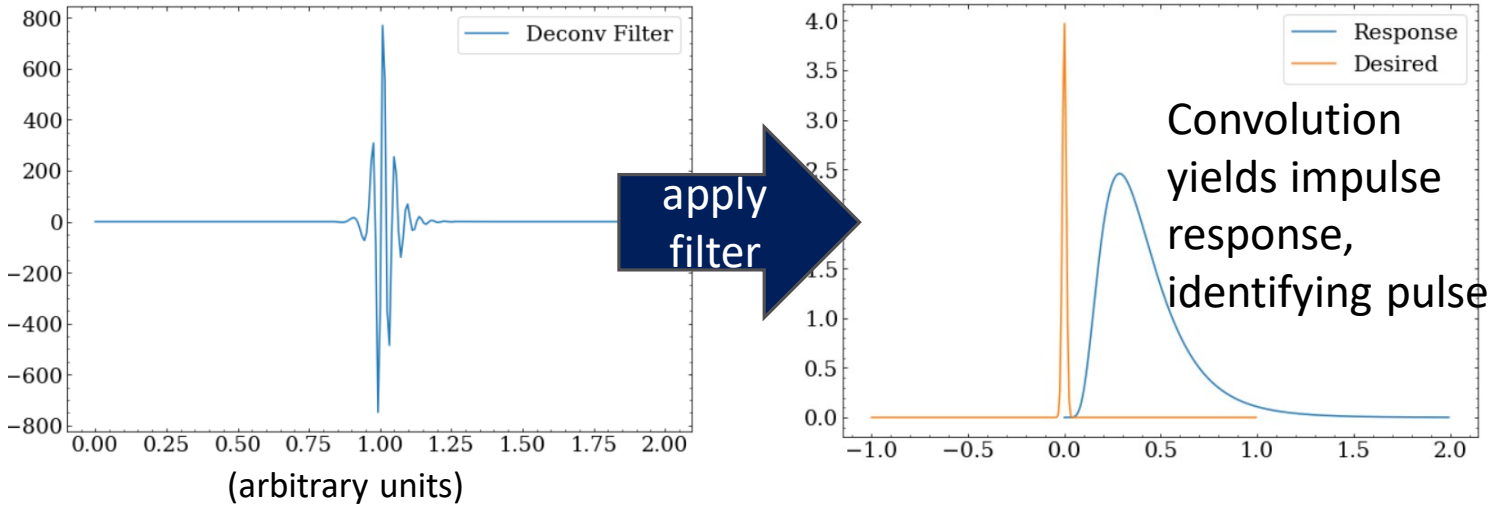


PE measurement and counting

- How can we determine #PEs ?
- Maximum likelihood estimation
  - Calculate 3-D probability density functions using TOT, Q, peak
  - Obtain good estimate of number of PE in a pulse for 1—8 PE
  - Proof of concept that we only need a few measurements
- Frequency domain
  - Convolve filter response of ideal log-normal pulse with input signal
  - Sensitive to filter kernel, aliasing problems
- Many other approaches: matched filter, interpolation, etc.
- Many approaches work best offline, or are difficult to implement with electronics

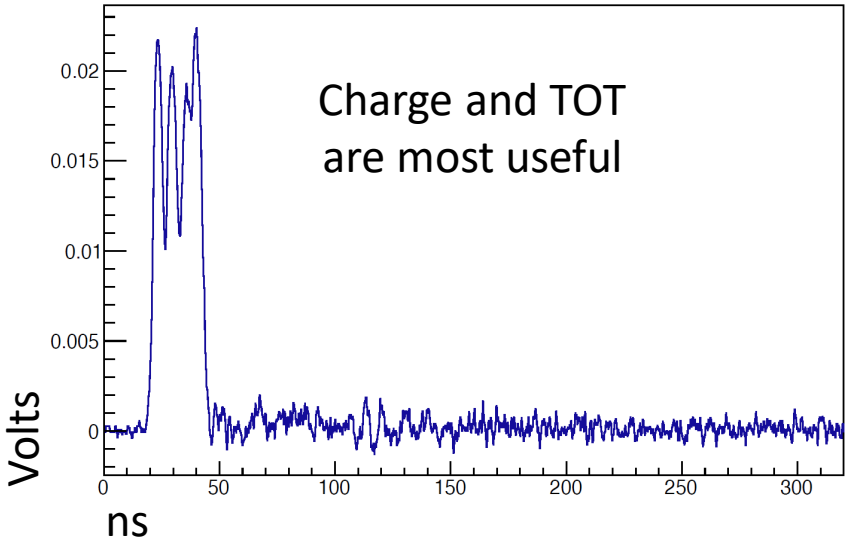


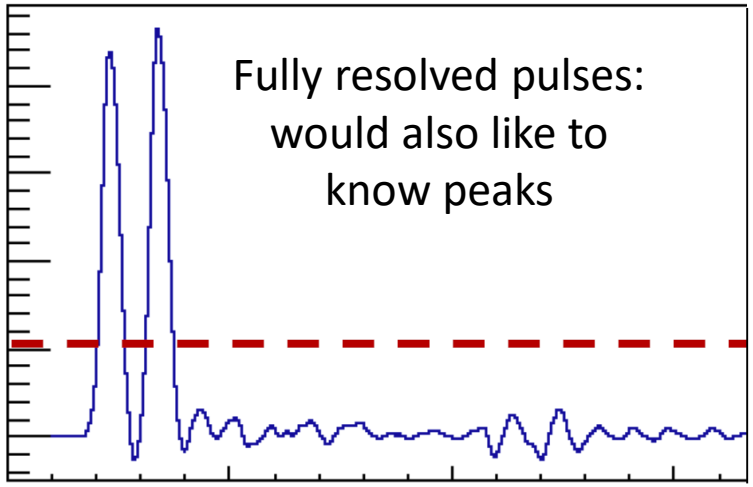




PE measurement and counting, cont.

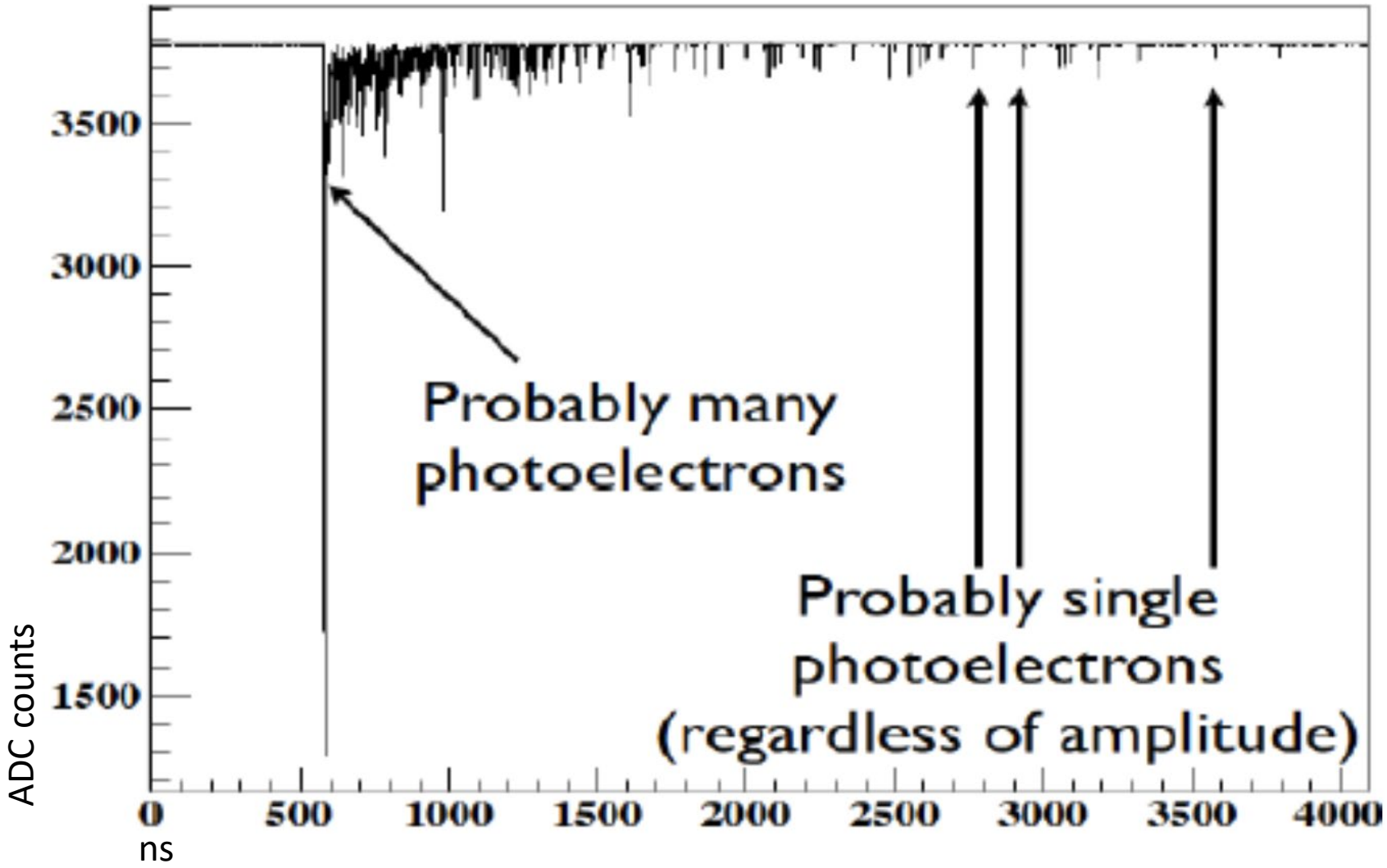
- We can do this with an ASIC, with local analog memory, read out with low cost ADC
- Analog circuit blocks
  - Peak detector
  - Integrator
  - Time to amplitude converter (TAC)
- SNO did this to some extent with TAC, charge (fixed windows)
  - No timing information on second hit
- Some older work in 0.35µm process
  - Not good for modern tubes with sub-ns TTS
- Some ASICs exist for this purpose, but “photon counting” mostly





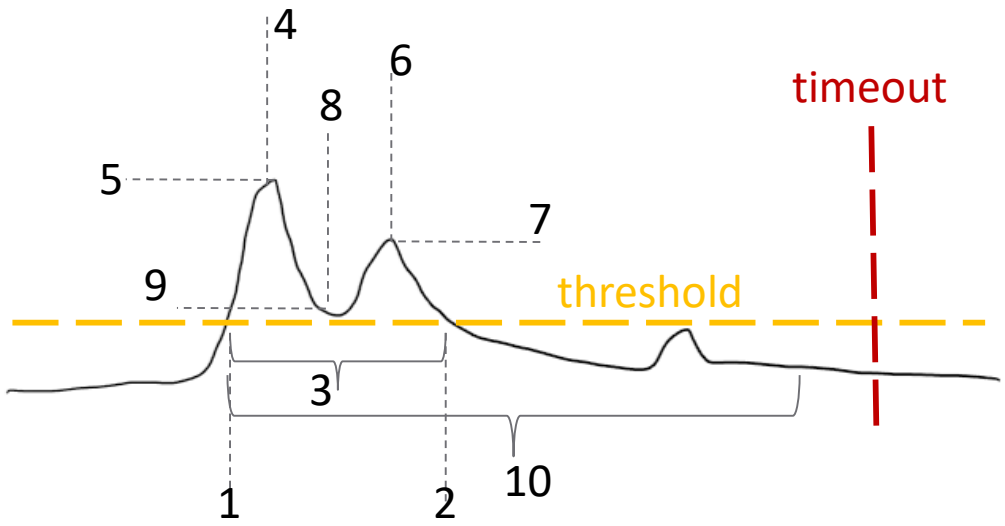
What happens in this case?

- Prompt region: Q gives good estimate of PE
- Tail region: PE counting more relevant
- We want:
  - Fast timing and large dynamic range for Cherenkov
  - Multi-PE resolution for scintillation



Basic requirements of APP

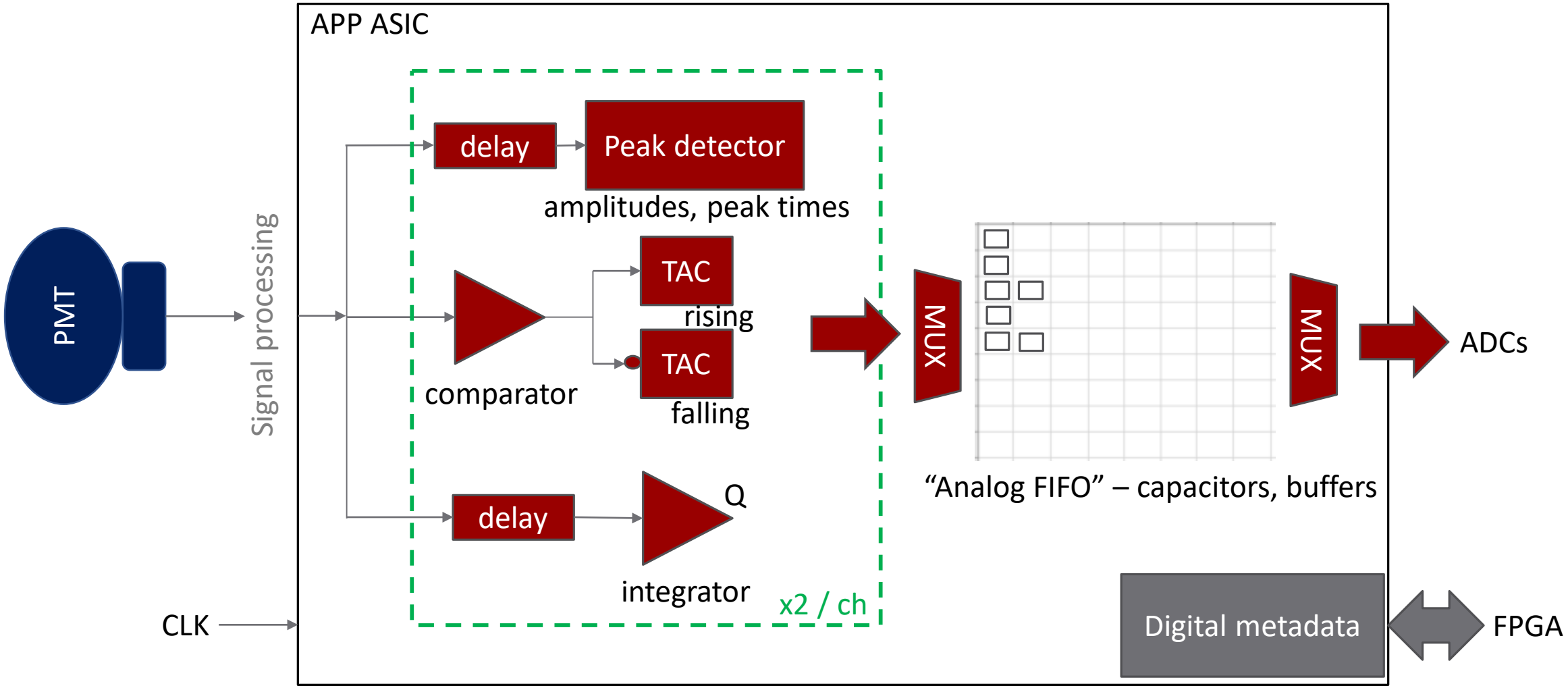
- We'd like to capture PMT pulses with:
  - Risetimes ~1ns or less
  - FWHM ~5ns or less
  - Better than 100ps timing (limited by TTS)
  - ~5—500mV amplitude (up to 100 PE)
    - After 50 PE, probably most information in Q
    - After 1000 PE, tube saturation
    - Motivates 2 gain paths
- Charge integral up to a few microseconds
  - Programmable window for "late" scintillation light
  - After a few unresolved PE, most information also in Q
- We want to re-trigger
  - To catch closely spaced resolved PE
  - Motivates "analog FIFO"
- 1—4 channel chip
  - Channel density probably limited by cables in a PMT system – not true for pixelated detectors!



1. Leading edge of TOT "event"
2. Trailing edge of TOT event
3. Integral of TOT event (charge)
4. Time of 1st peak in the event
5. Amplitude of 1st peak in the event
6. Time of 2nd peak in the event
7. Amplitude of 2nd peak in the event
8. Time of 1st valley in the event
9. Amplitude of 2nd valley in the event
10. Integral of total charge over a programmable time starting with the 1st event

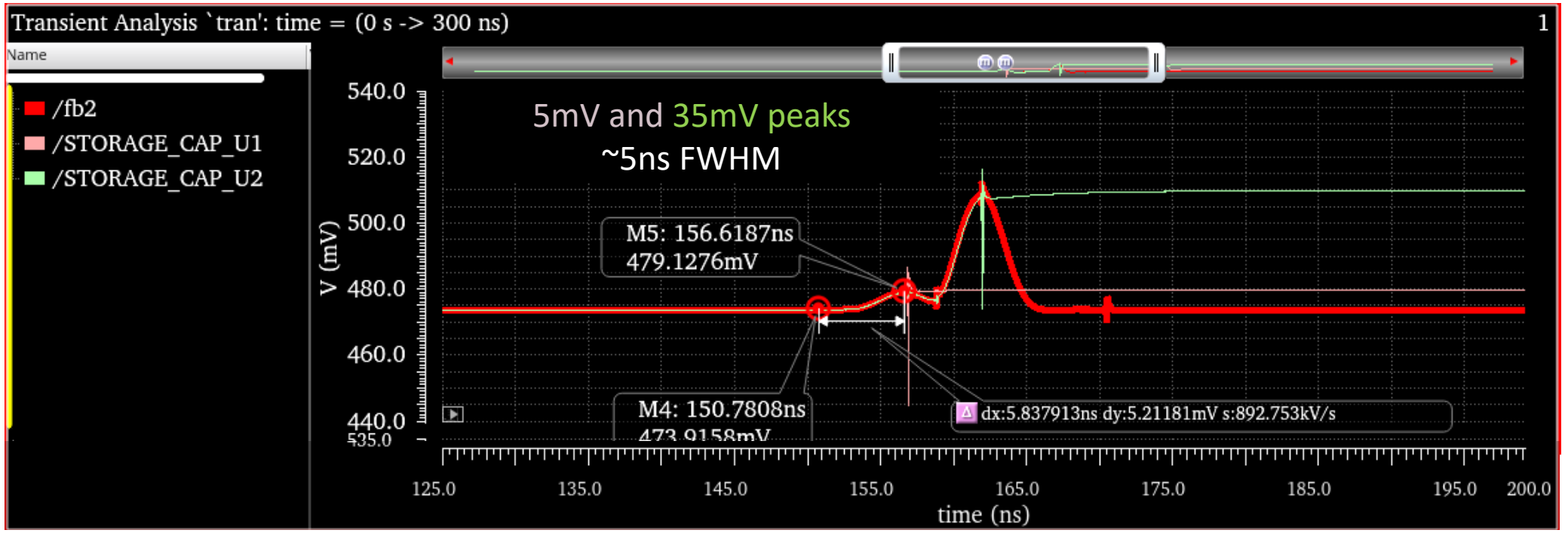
(Not every measurement needed for every application)

Block diagram (very simplified)



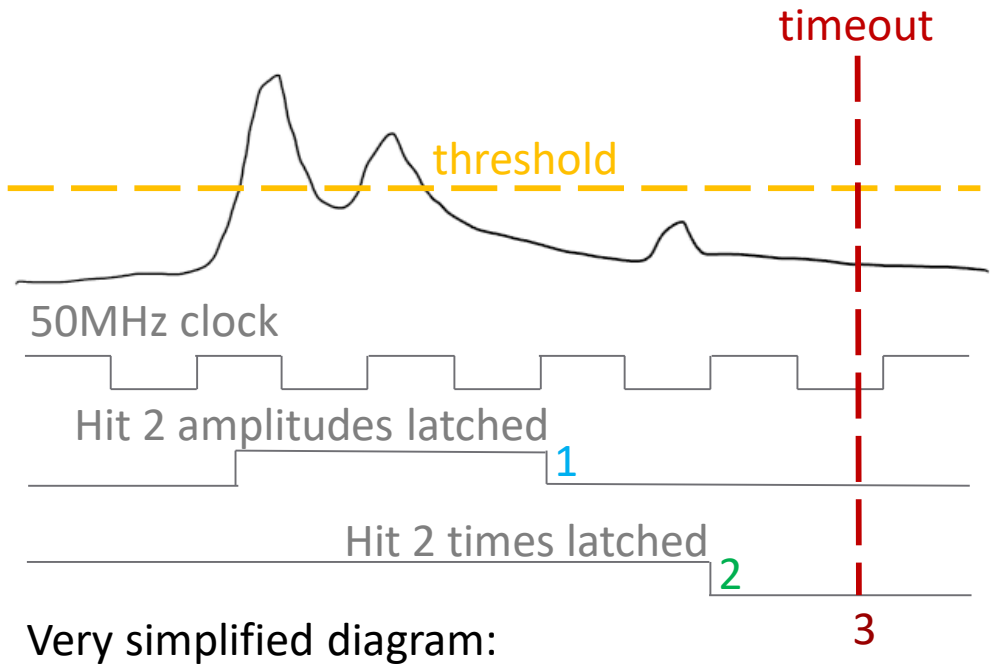
Peak detector circuit simulation

- Using TSMC 65nm process

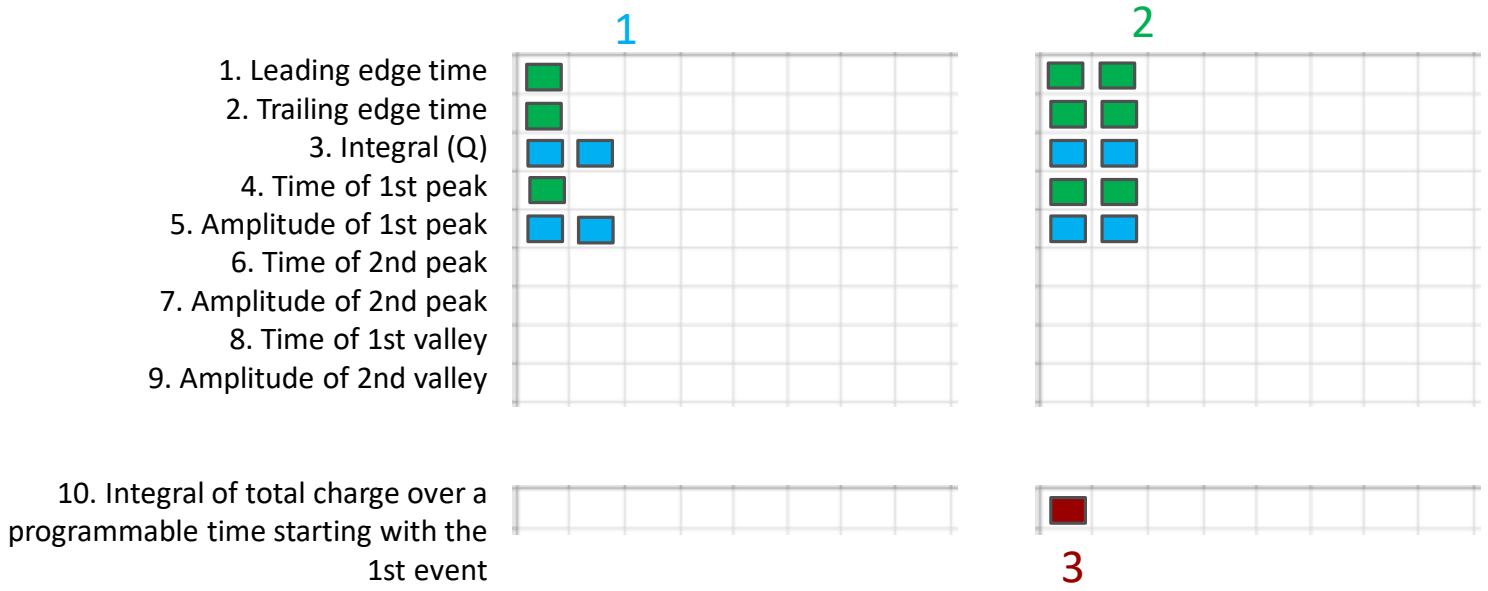


Example #1

- Ping-pong architecture can store 2 closely spaced peaks
  - Second peak is counted as a separate event, and measurements #6—9 are not stored
  - The “long charge” measurement #10 is always a separate analog memory



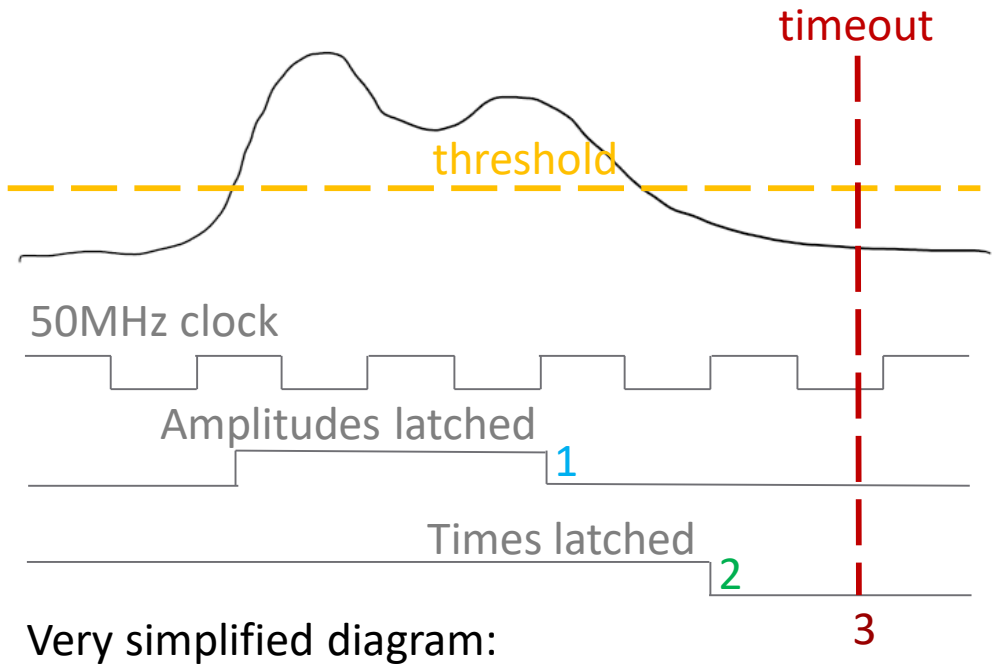
Very simplified diagram:
3 sample snapshots of analog memory shown
(not all signals shown)



Metadata:
b111110000 – valid memory locations
4 **timestamps** – leading/trailing edge
1 **timestamp** – “long charge”

Example #2

- Ping-pong architecture can store 2 closely spaced peaks
  - Second peak is counted as a separate event, and measurements #6—9 are not stored
  - The “long charge” measurement #10 is always a separate analog memory
  - If a second peak is never resolved, measurements #6—9 are stored



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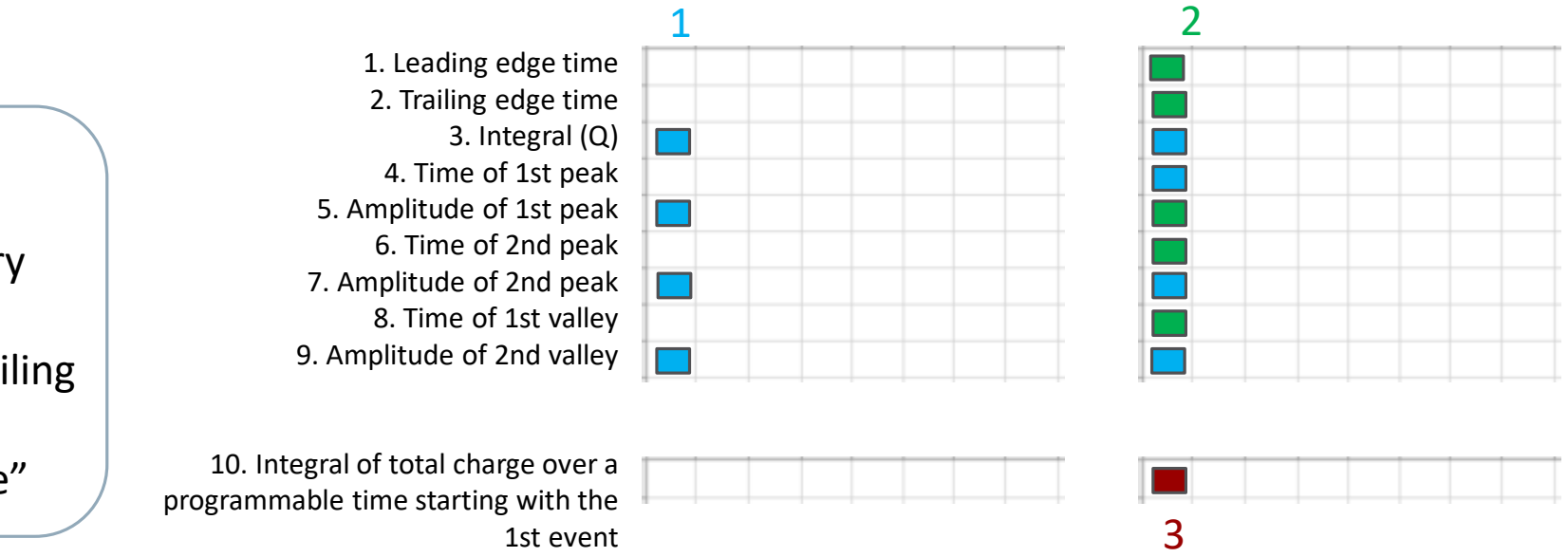
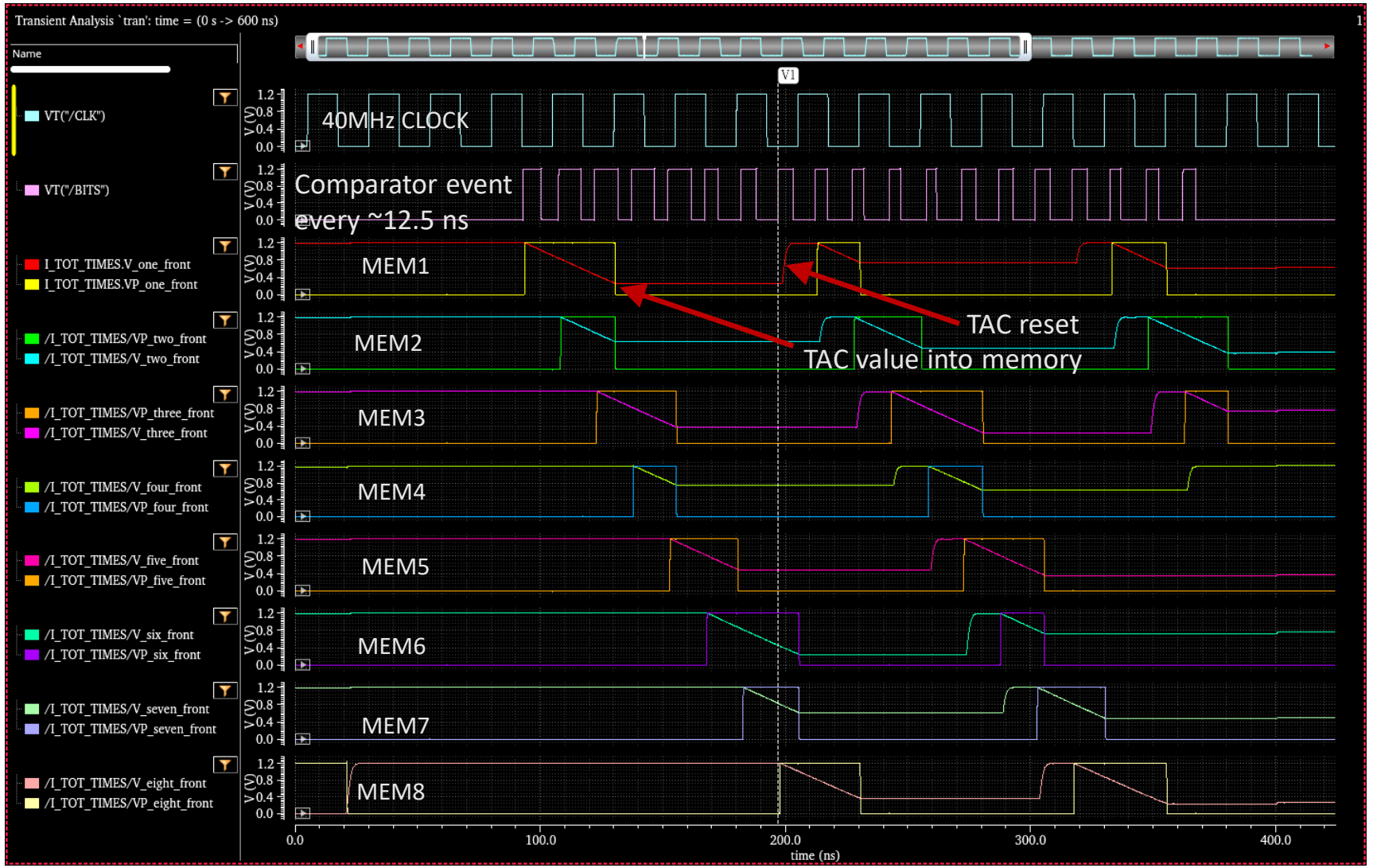
3 sample snapshots of analog memory shown (not all signals shown)



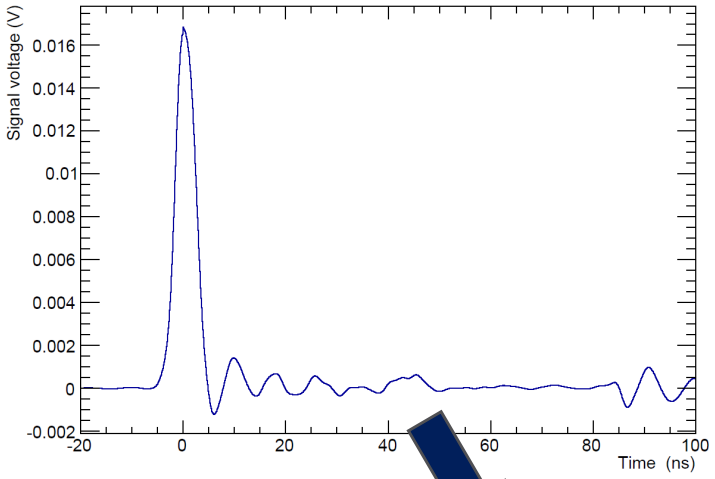
Metadata:
b111111111 – valid memory locations
2 **timestamps** – leading/trailing edge
1 **timestamp** – “long charge”

Full channel analog simulation

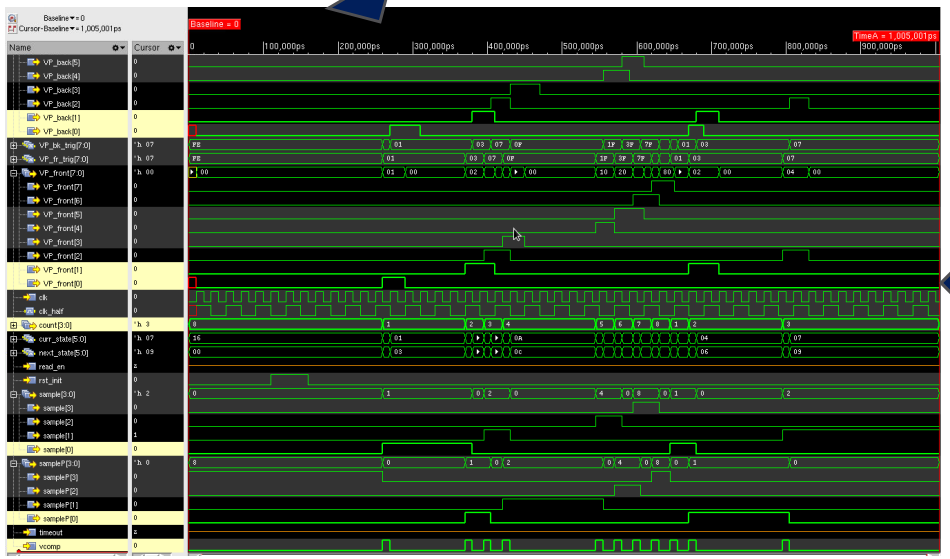
8 memories filled in circular buffer mode



cocotb simulation flow



Real data, converted to .csv and fed into simulator



Behavioral model of analog blocks – fast simulation time

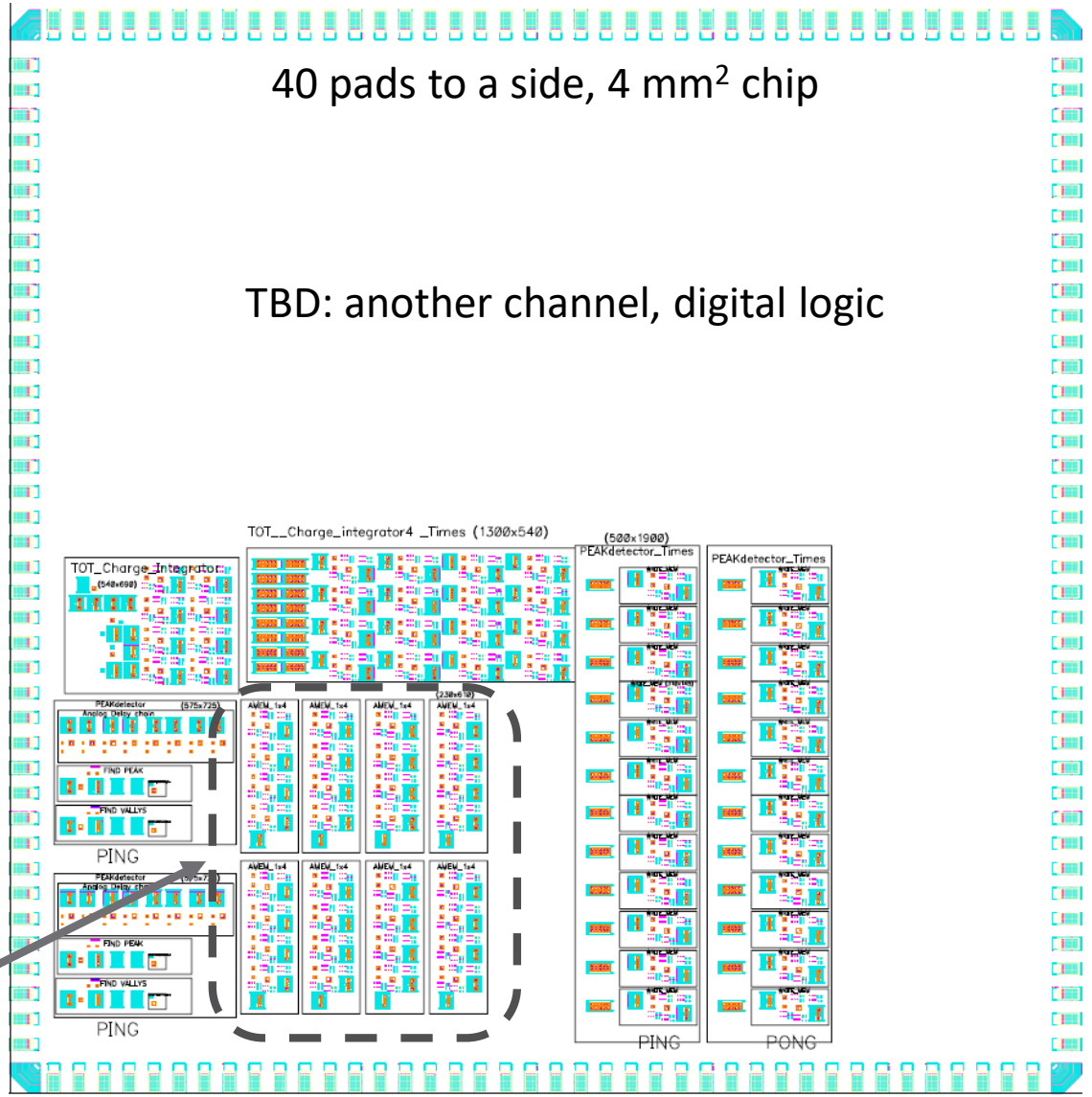
- cocotb is a simulation framework that allows one to use Python to write testbenches
- Used successfully in the design and verification of ITK ASICs

Internal logic

```
// signals to/from outside world
input wire clk,
input wire resetb_full,
input wire adc_ready,
input wire adc_done,
input wire circular_en,
input wire read_next,
output wire amem_empty,
output wire amem_full
```

FPGA

Preliminary area estimate

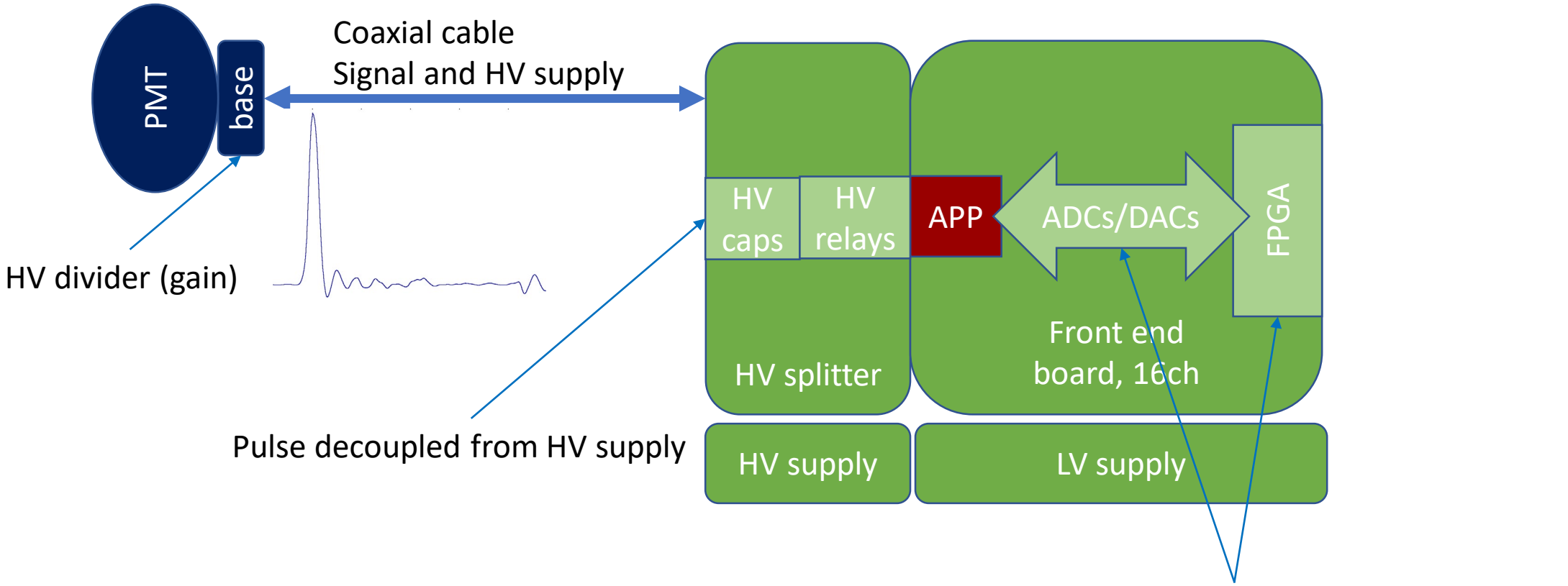


PMT inputs

Analog FIFOs

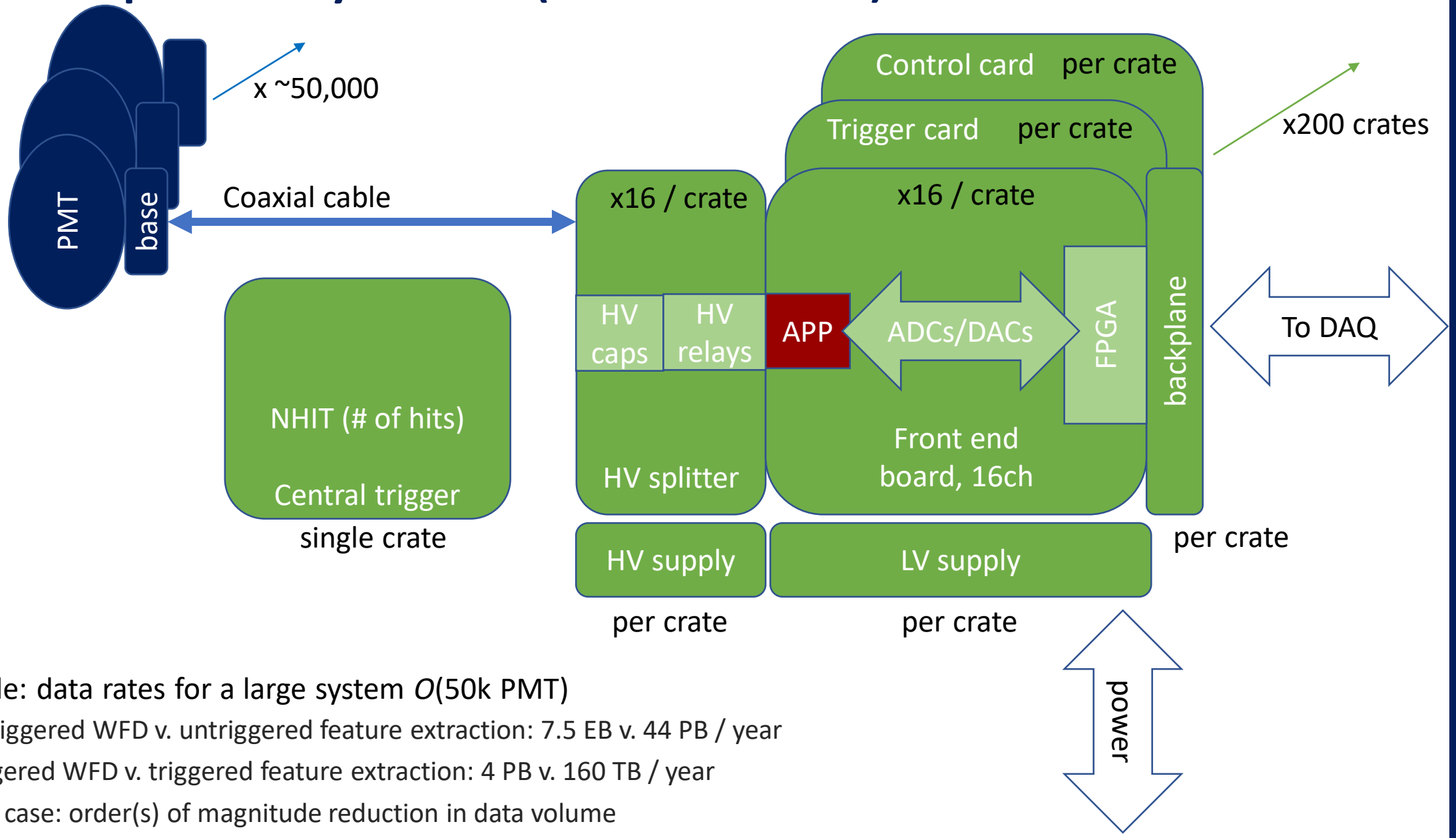
Analog measurements out (differential)

Conceptual system (a few channels)



Commercial readout
Low cost commercial ADCs (several $ per channel)

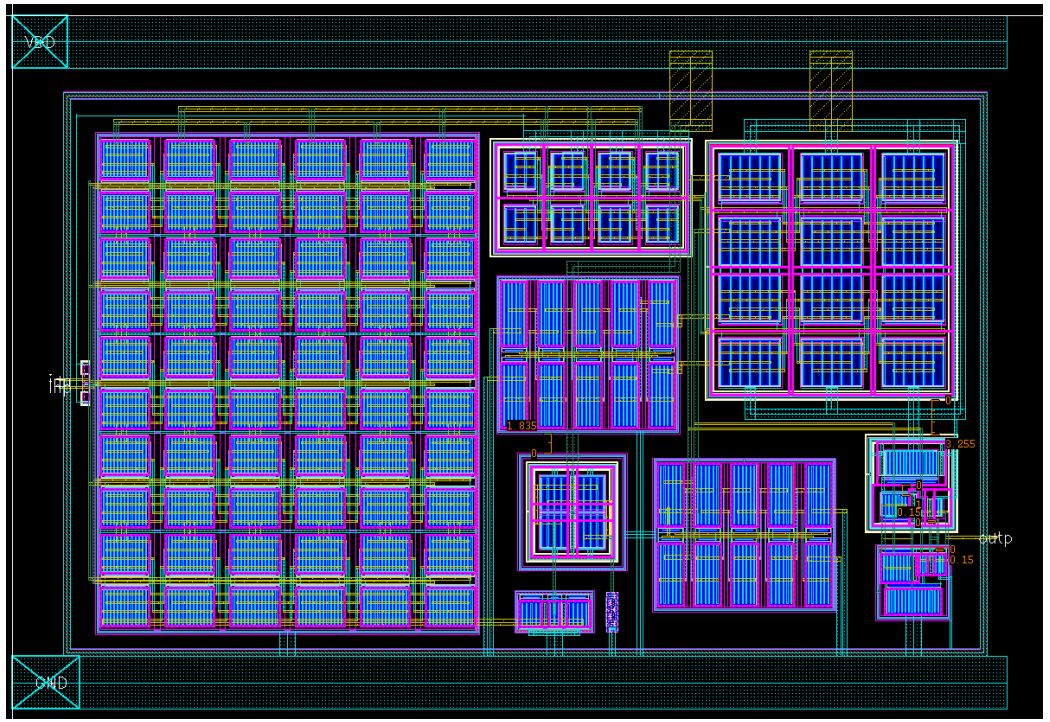
Conceptual system (a detector)



- Example: data rates for a large system *O*(50k PMT)
  - Untriggered WFD v. untriggered feature extraction: 7.5 EB v. 44 PB / year
  - Triggered WFD v. triggered feature extraction: 4 PB v. 160 TB / year
  - Best case: order(s) of magnitude reduction in data volume

Next steps

- Many APP analog blocks are complete or nearly complete
- Digital logic being written/simulated
- We are designing a test structure/demonstrator for APP:
  - Commercial FPGA, Ethernet readout
  - 14 bit commercial ADCs with convert trigger, not continuous sampling (ENOB closer to ~12b, really only need 8—10b)
    - ~300 uV / count
    - sub 10ps TAC resolution
    - Probably limited by digitization time
  - Support: calibration, analog sum, trigger, etc.



Example fast comparator layout

Thank you!

- Current APP team: Nandor Dressnandt[2], Paul Keener[2], Josh Klein[1], Yiming He[4], Max Malakhovets[5], Godwin Mayers[2] , Mitch Newcomer[2], Adrian Nikolica[2], Ravi Pitelka[3], Rick Van Berg[2], Jihao Yang[4]
- Past contributors: Bill Heintzelman[7], Ben Land[6], Chengjun Li[4], Xiaokai Ma[4], Meijun Tian[4] , Hao Yan[4]

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