DOMs and the DAQ Demystified
Part I: DOMs

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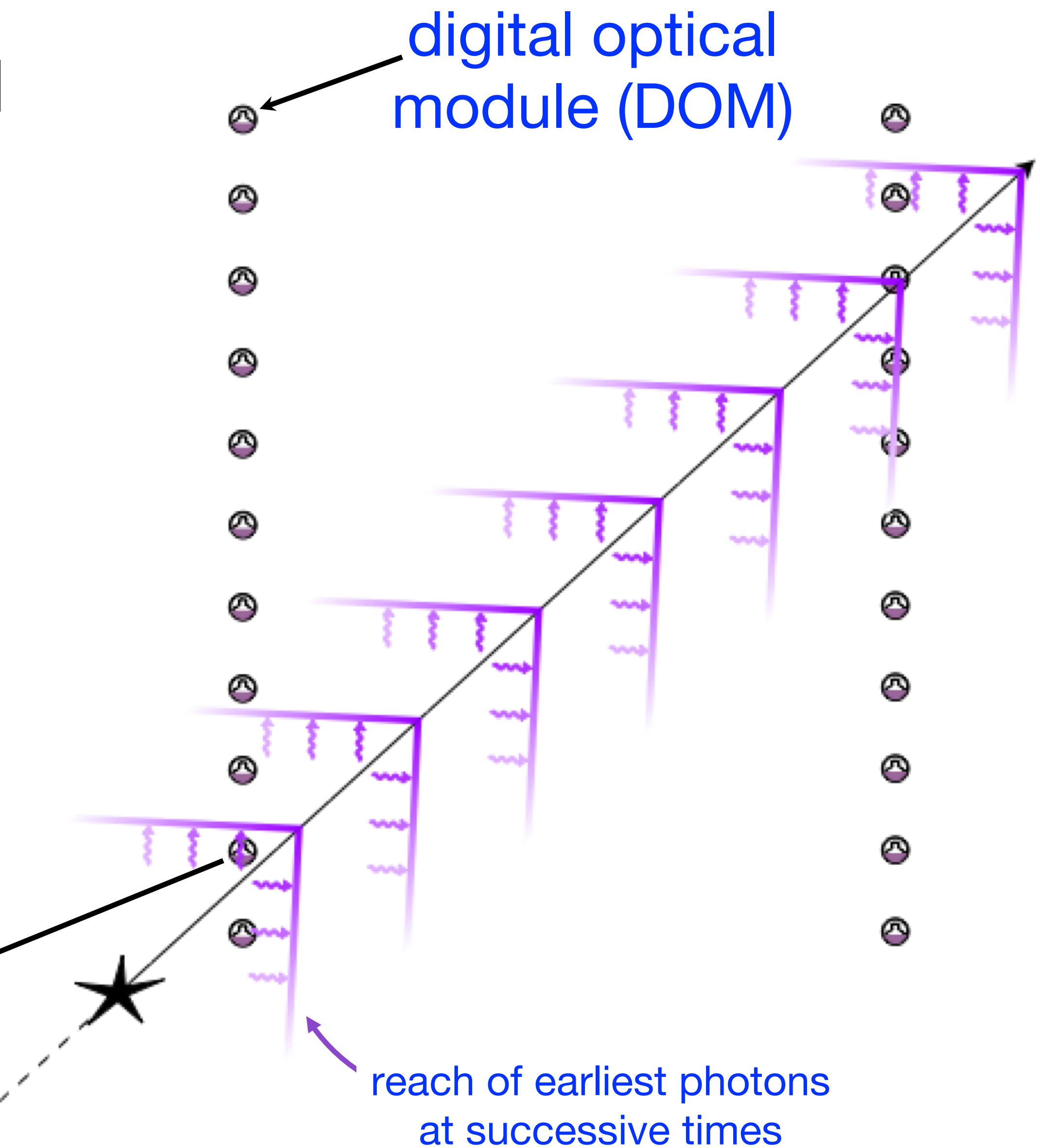
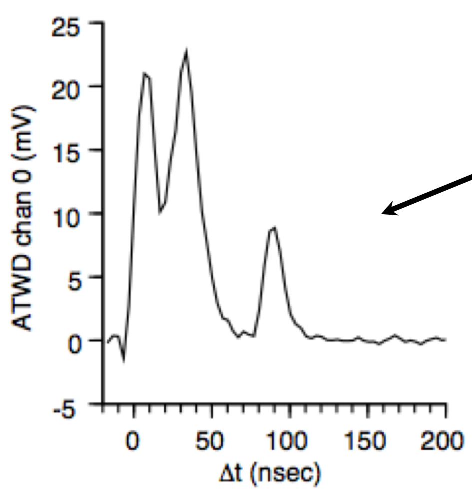
IceCube Bootcamp, 2018-06-19

with thanks to Chris Wendt

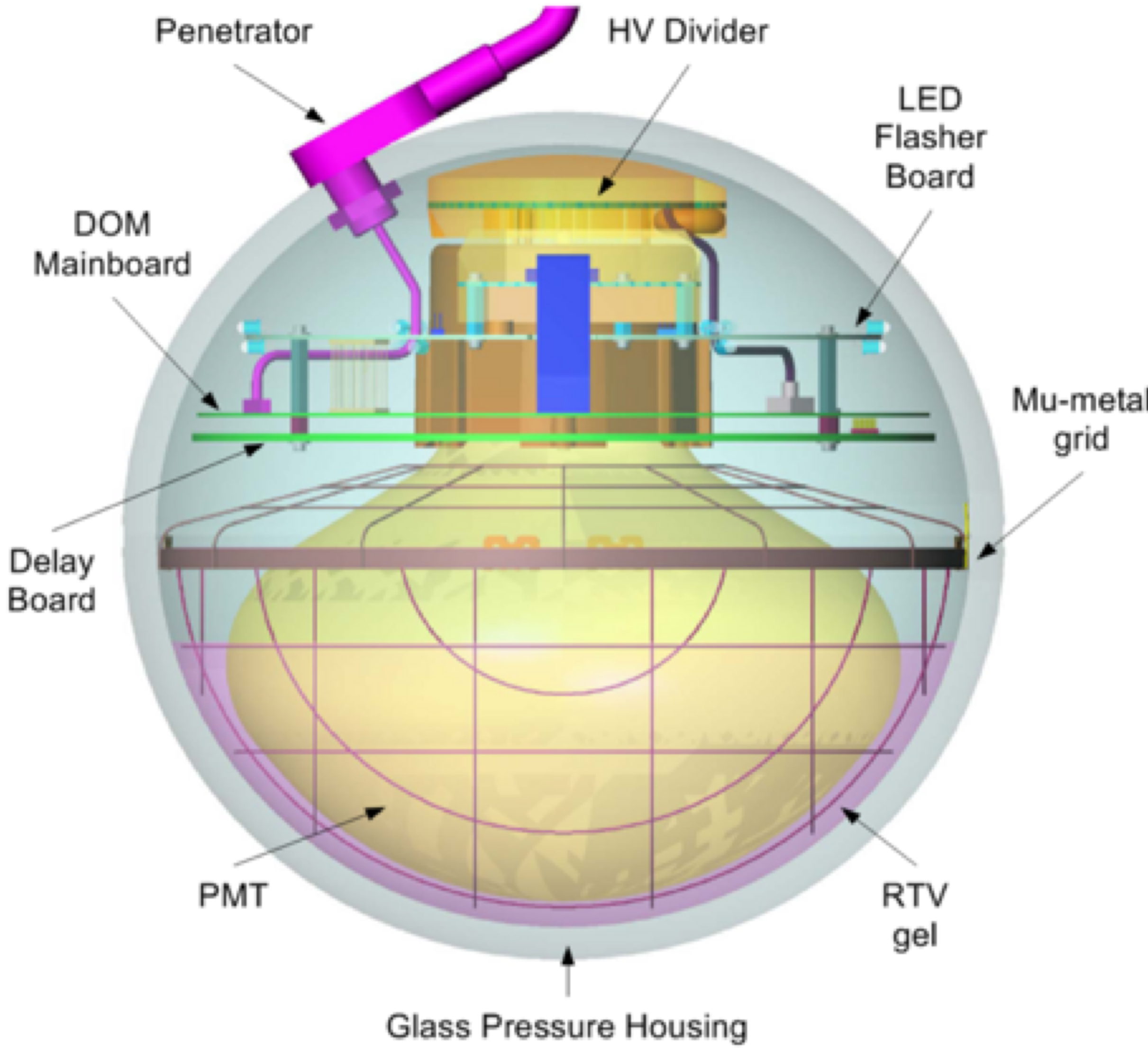
$\nu_\mu \rightarrow \mu$ Detection

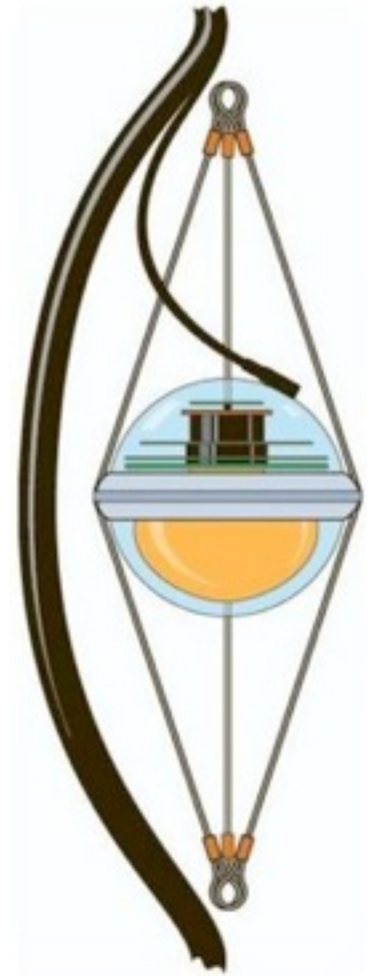
- Light is mostly emitted in small bursts along muon track
- Photon arrival times, and how many there are, tell us the direction and the energy of the muon





What's in a DOM?

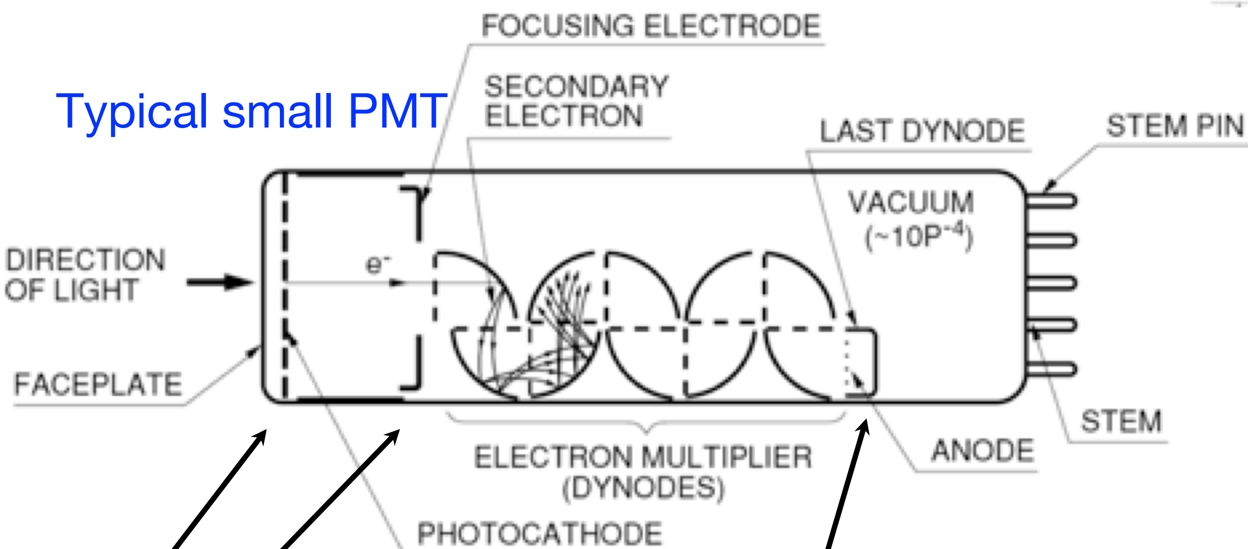


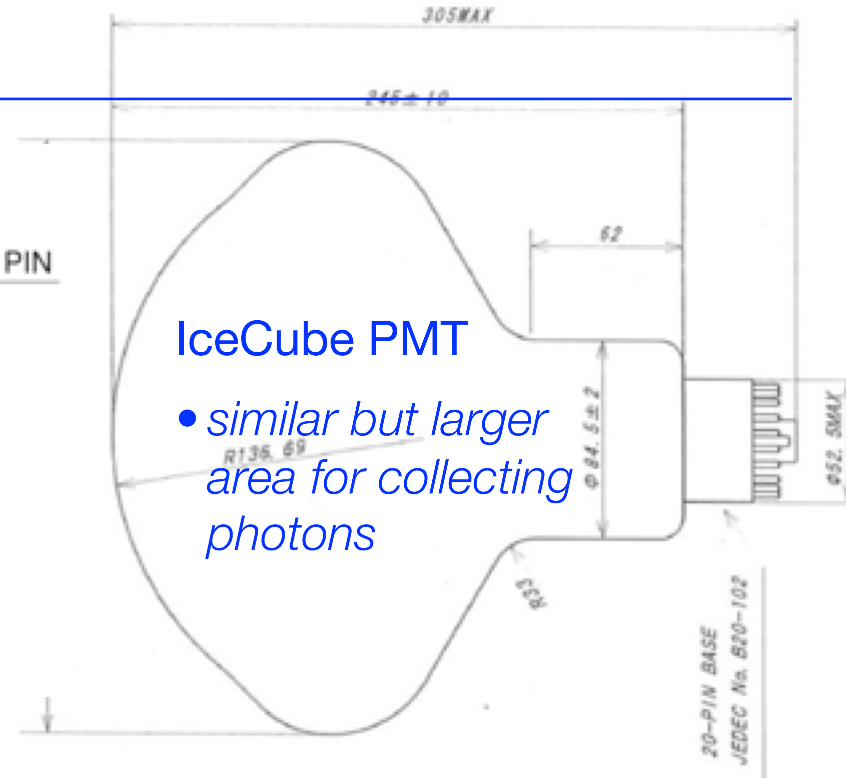


Cable: many twisted pairs, each pair carries power & communications for 2 DOMs

Photomultiplier Tube (PMT)

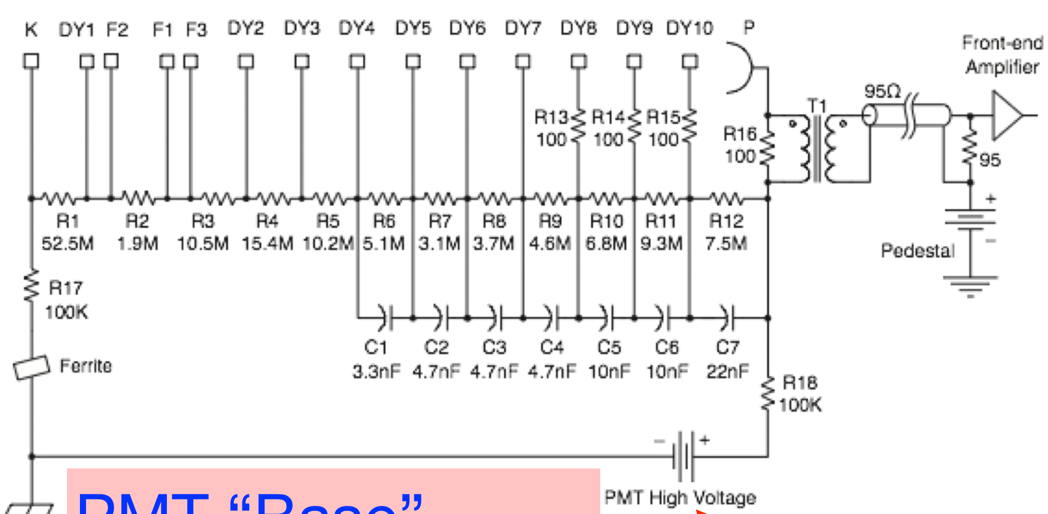
Typical small PMT





IceCube PMT

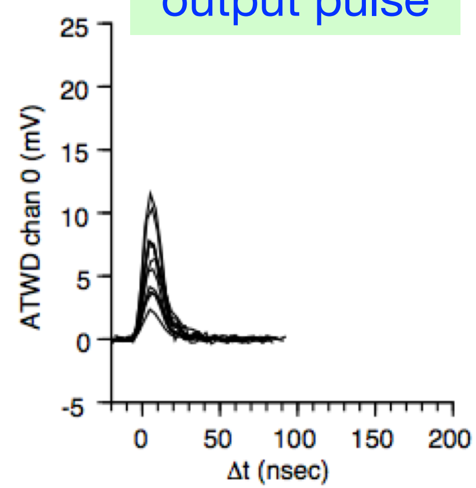
- *similar but larger area for collecting photons*



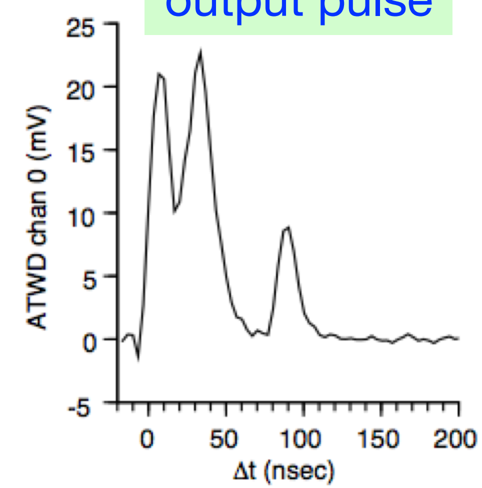
PMT "Base"
= Voltage Divider

~1500 volts

Single photon output pulse

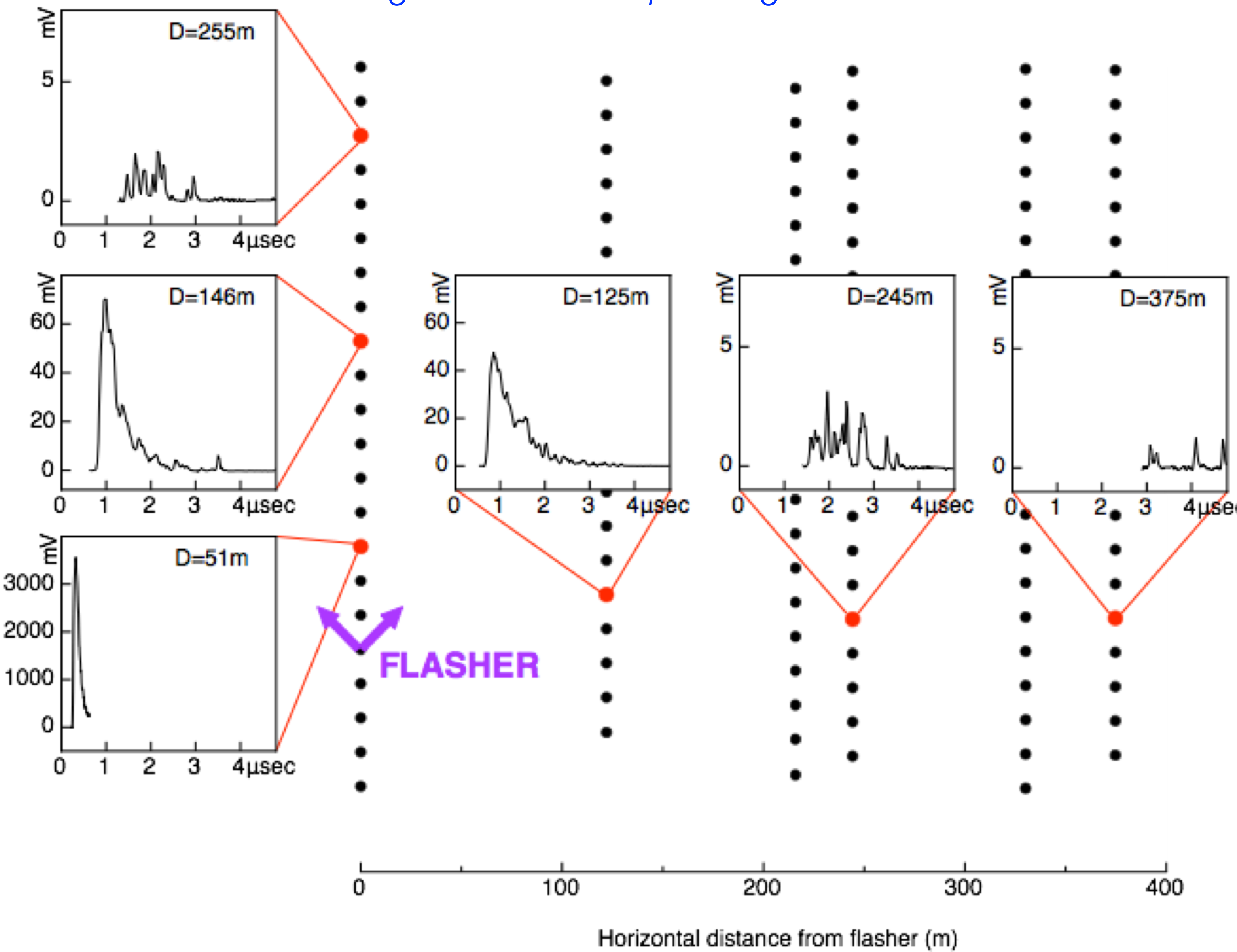


Multi-photon output pulse



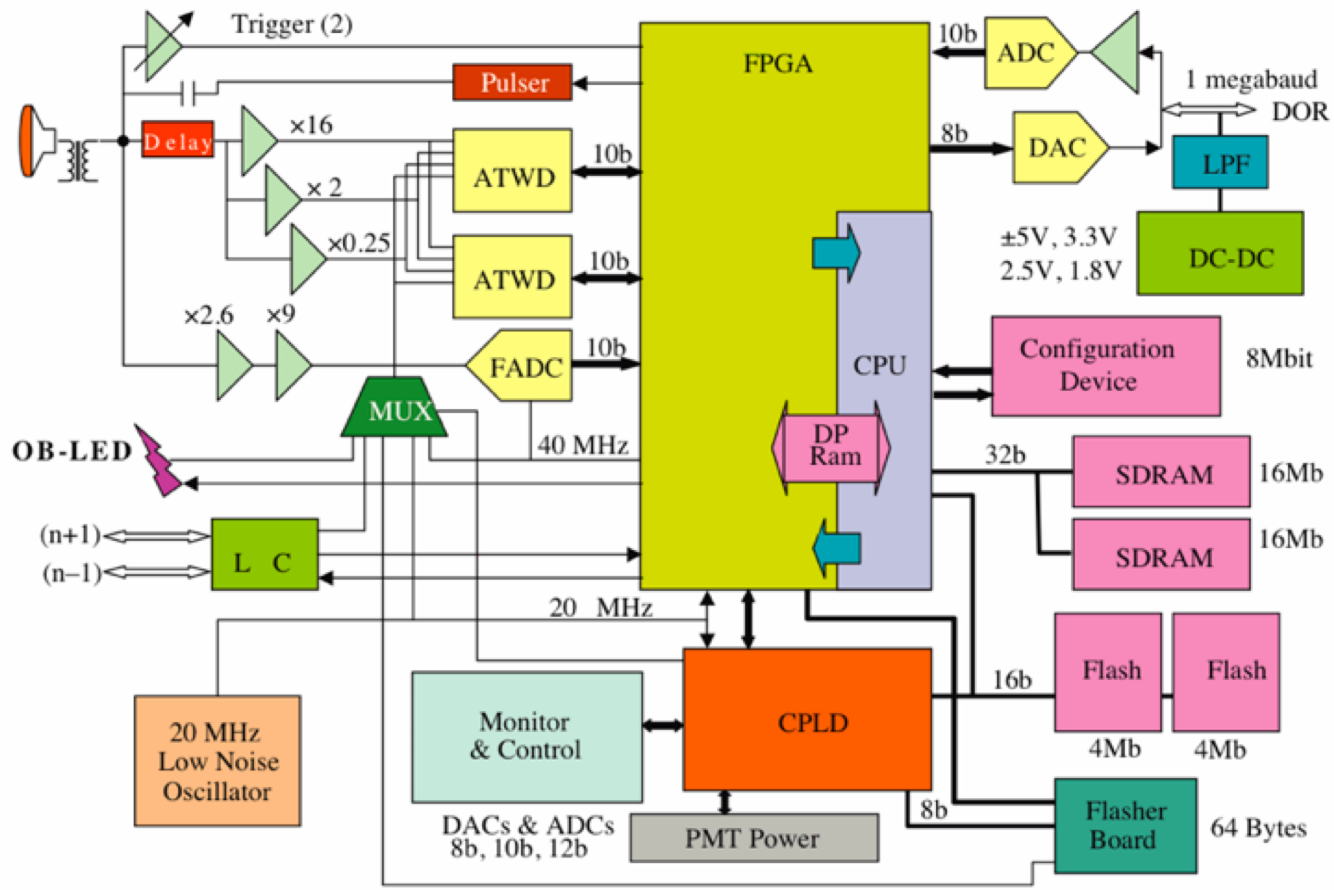
DOM signals resulting from localized light flash

- *Big differences depending on distance from source*



DOM Main Board

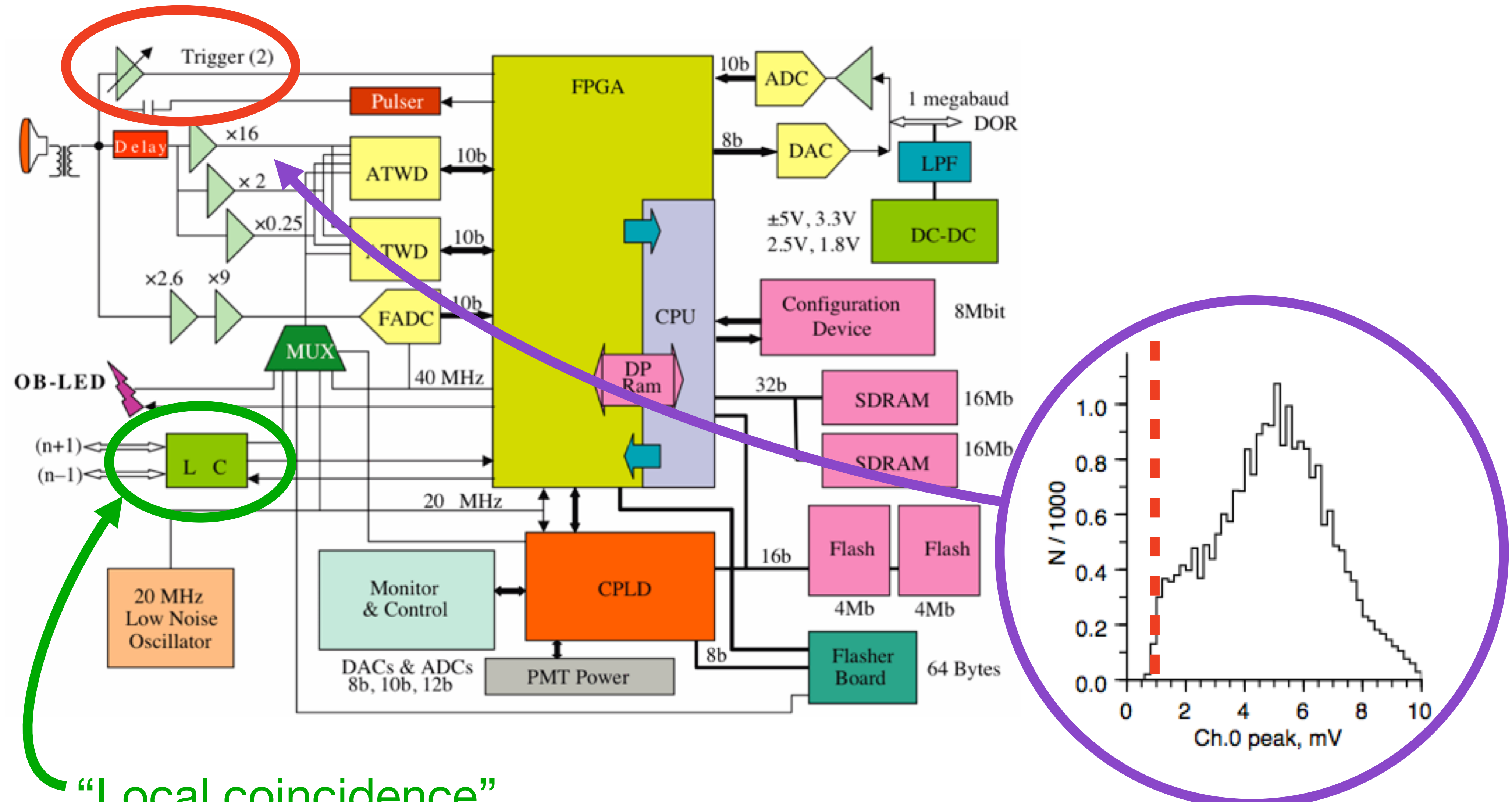
Contains waveform digitizers, on-board computer, communications circuits, HV & flasher control, etc.



[“The IceCube Data Acquisition Subsystem: Signal Capture, Digitization, and Time-Stamping”](https://docushare.icecube.wisc.edu/dsweb/Get/Document-48249/)
Nuclear Instruments and Methods in Physics Research A 601 (2009) 294–316
https://docushare.icecube.wisc.edu/dsweb/Get/Document-48249/

Triggering on single photons

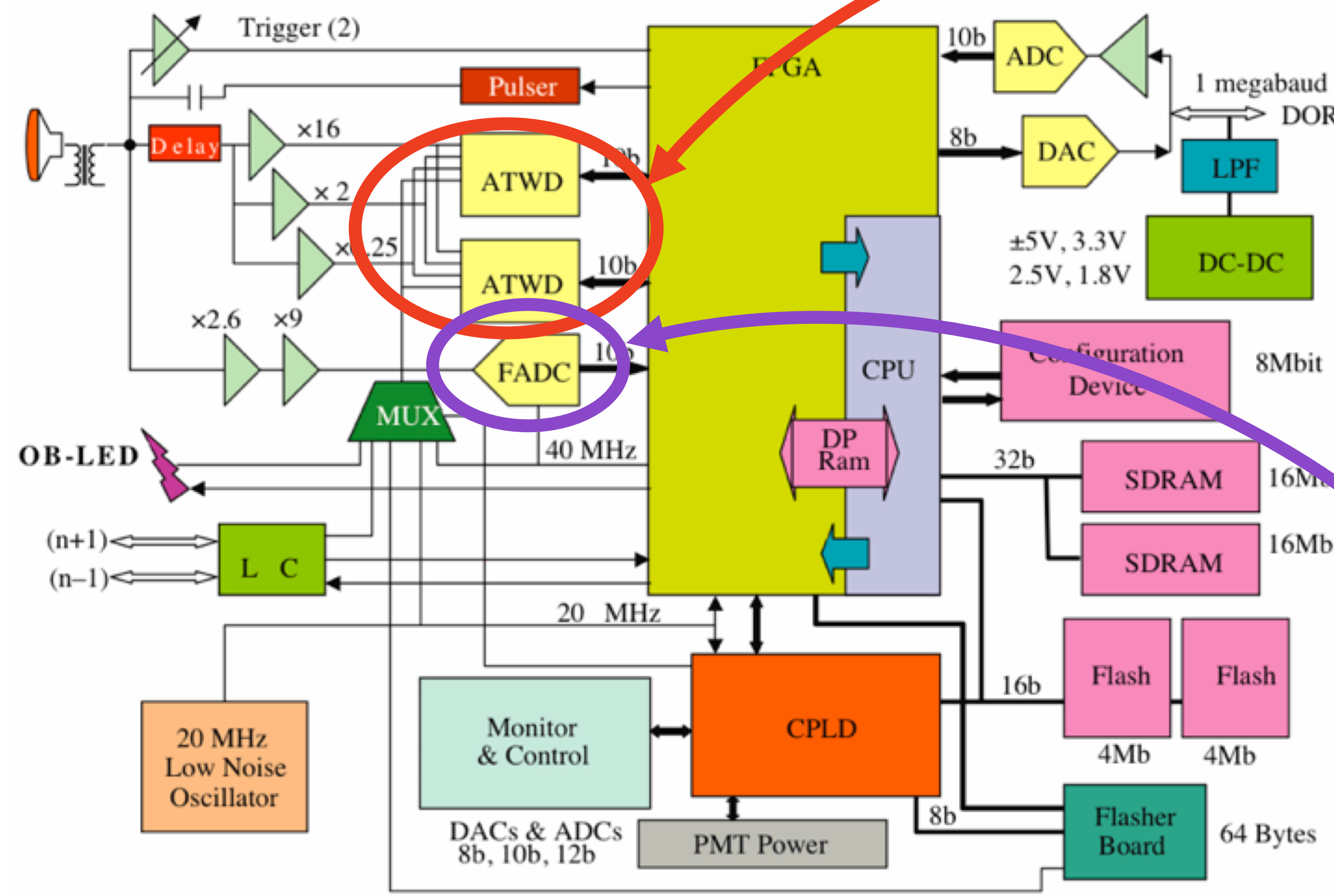
Actually single photoelectrons, “SPEs”



“Local coincidence”

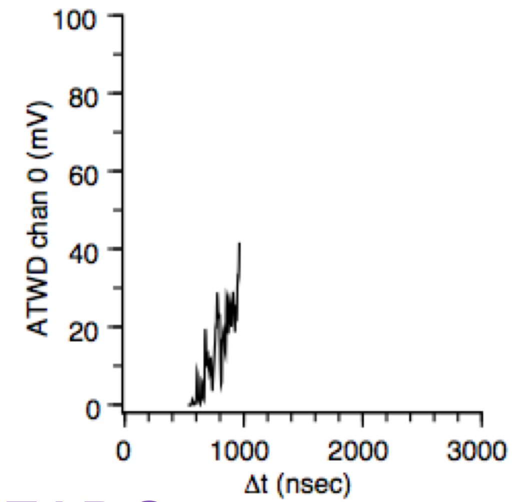
- *looks at whether a nearby DOM also recorded an SPE*

Waveform recorders (digitizers)



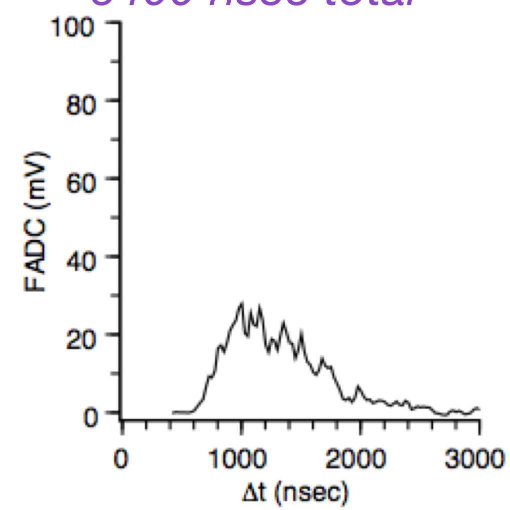
ATWD (2 in parallel)

- 3.3 nsec samples
- 427 nsec total



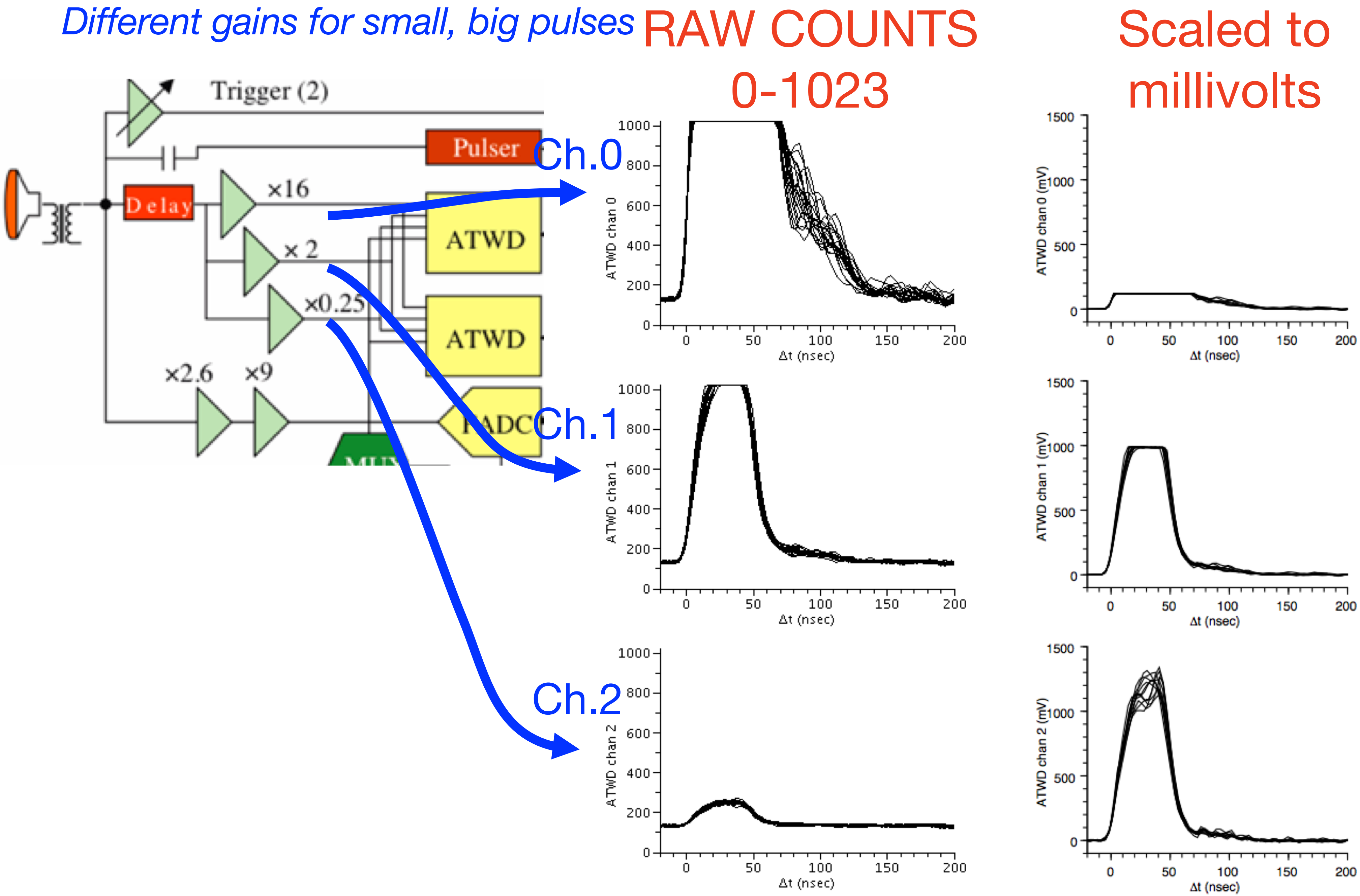
FADC

- 25 nsec samples
- 6400 nsec total



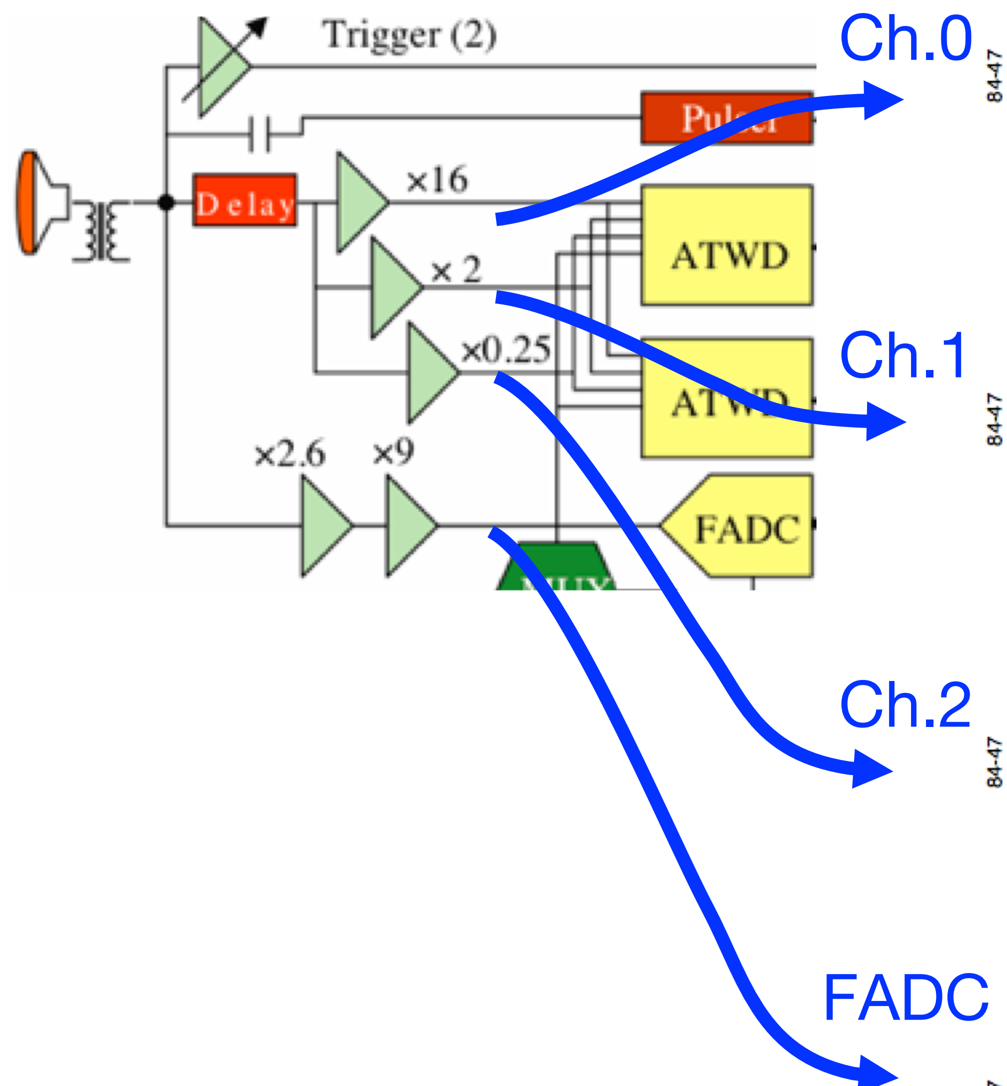
Waveform digitizers “ATWD” Channel 0,1,2

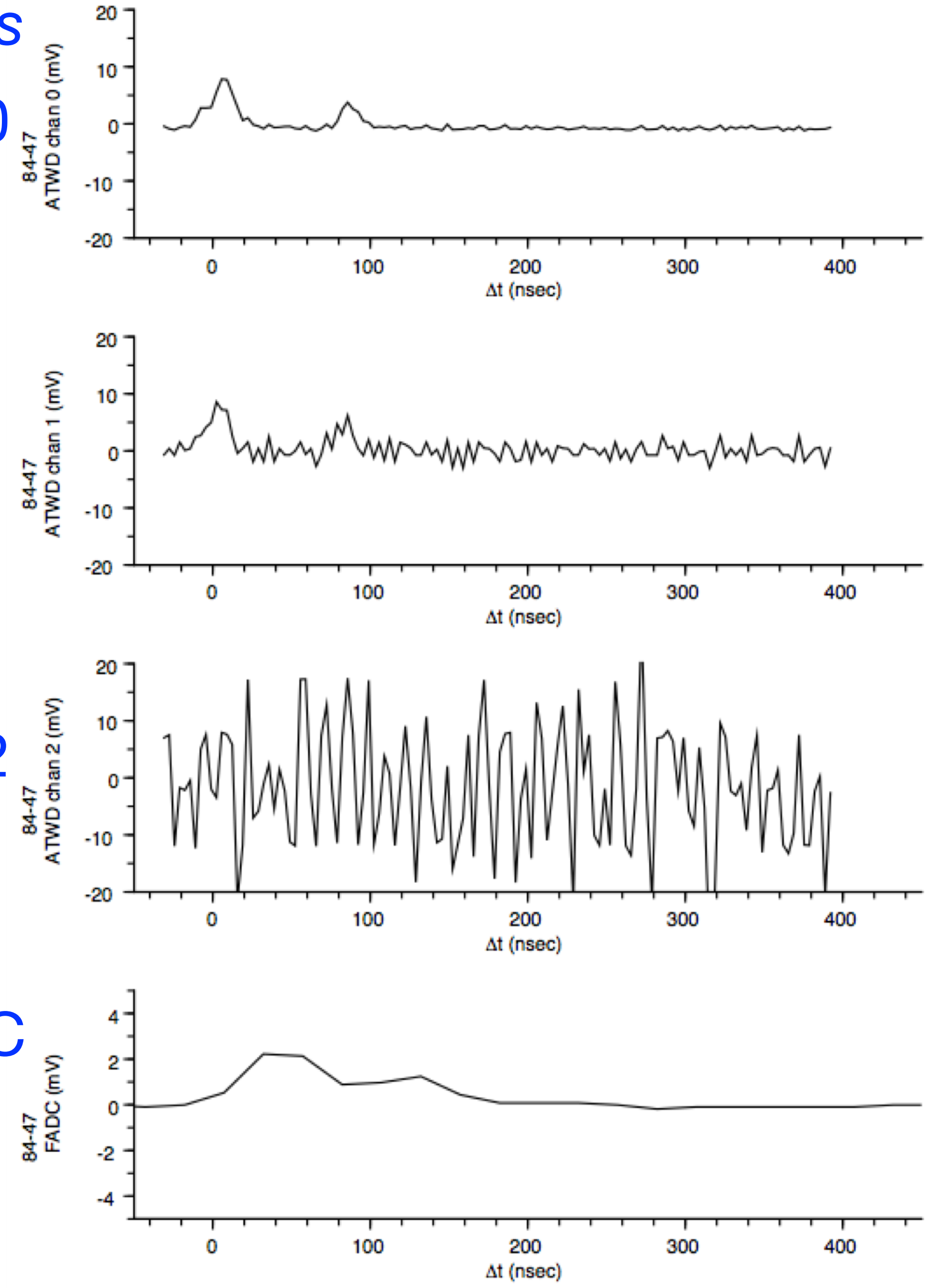
Different gains for small, big pulses



Waveform digitizers “ATWD” Ch. 0,1,2 and “FADC”

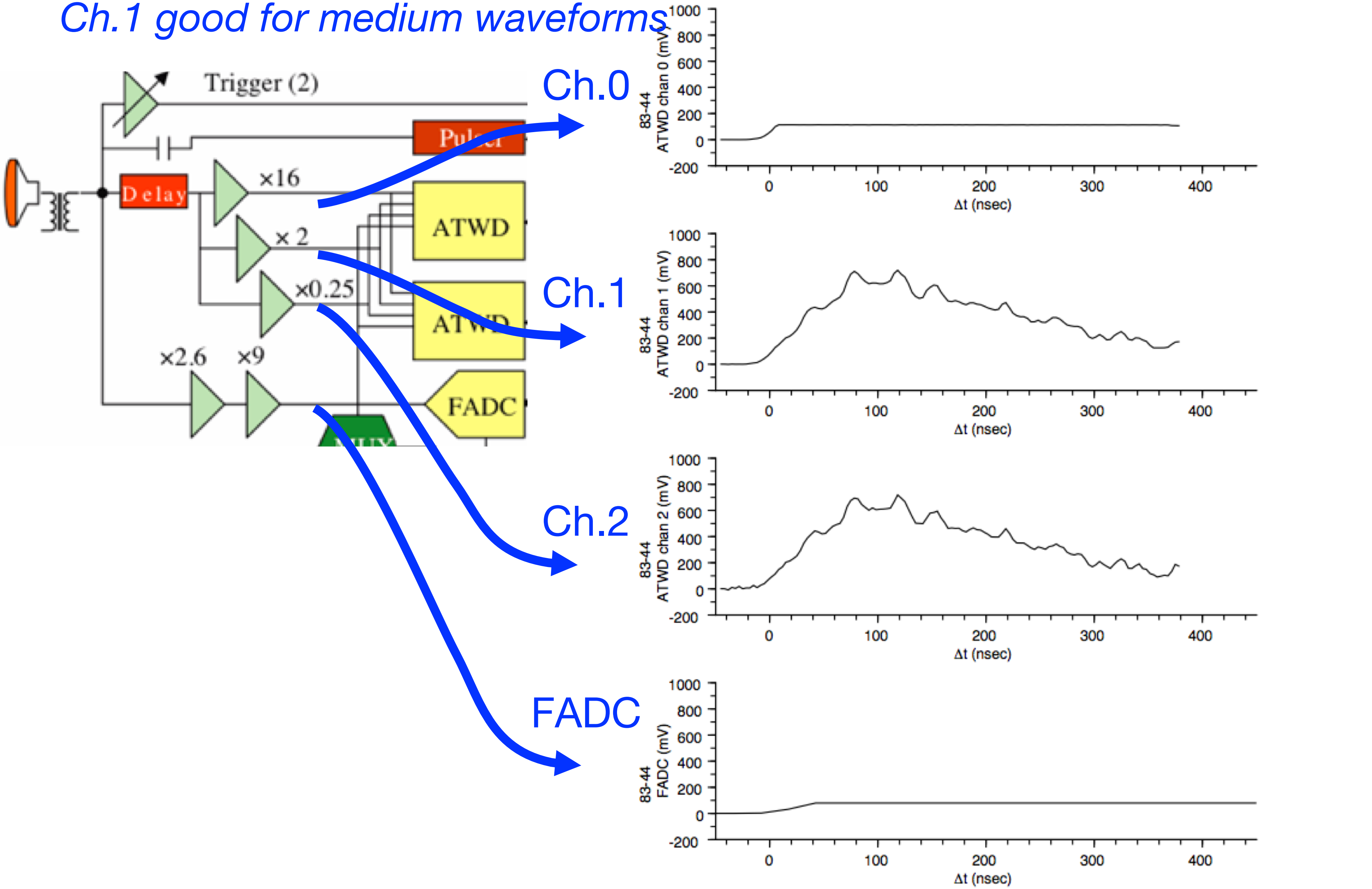
Ch.0 good for small waveforms





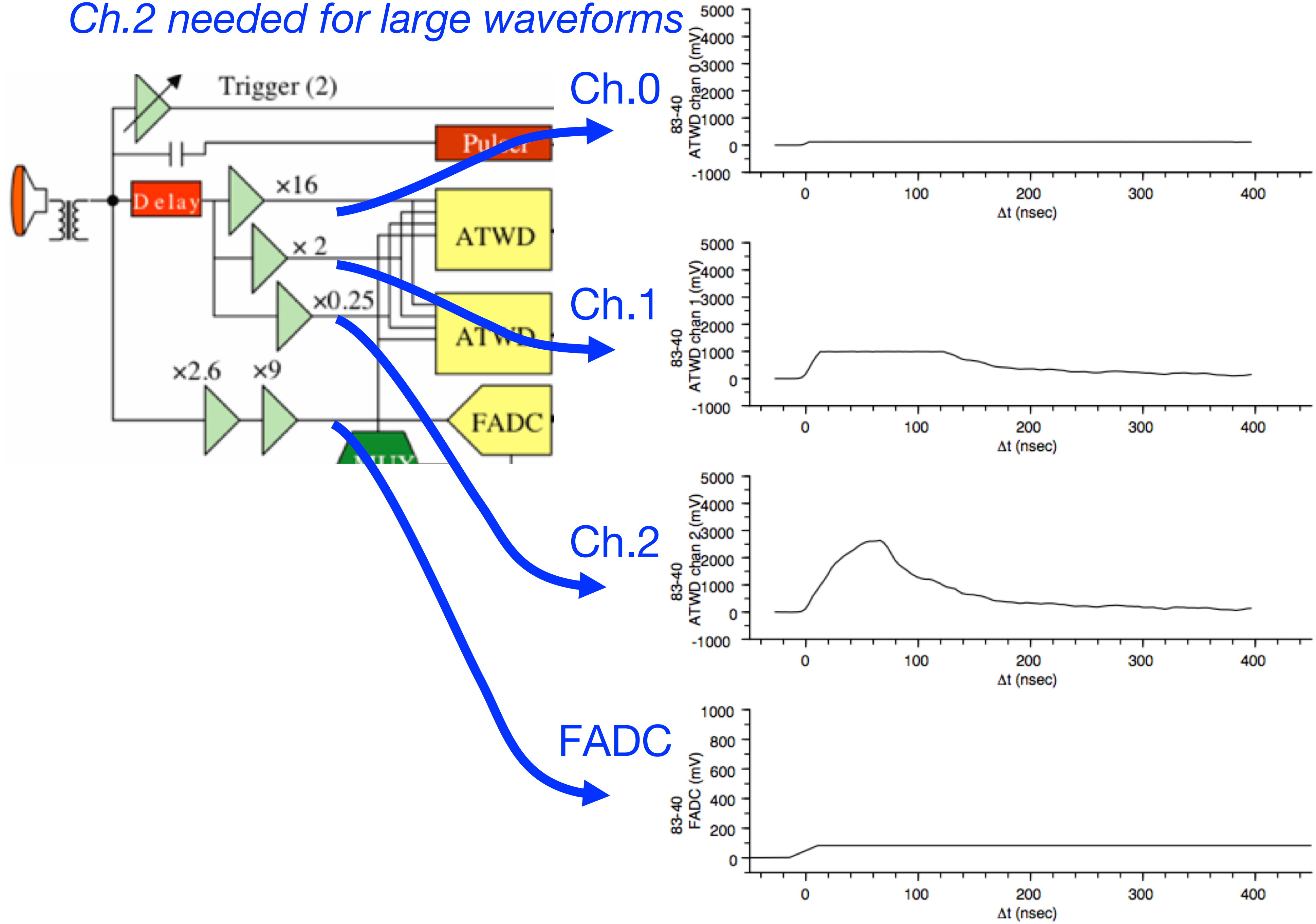
Waveform digitizers “ATWD” Ch. 0,1,2 and “FADC”

Ch.1 good for medium waveforms



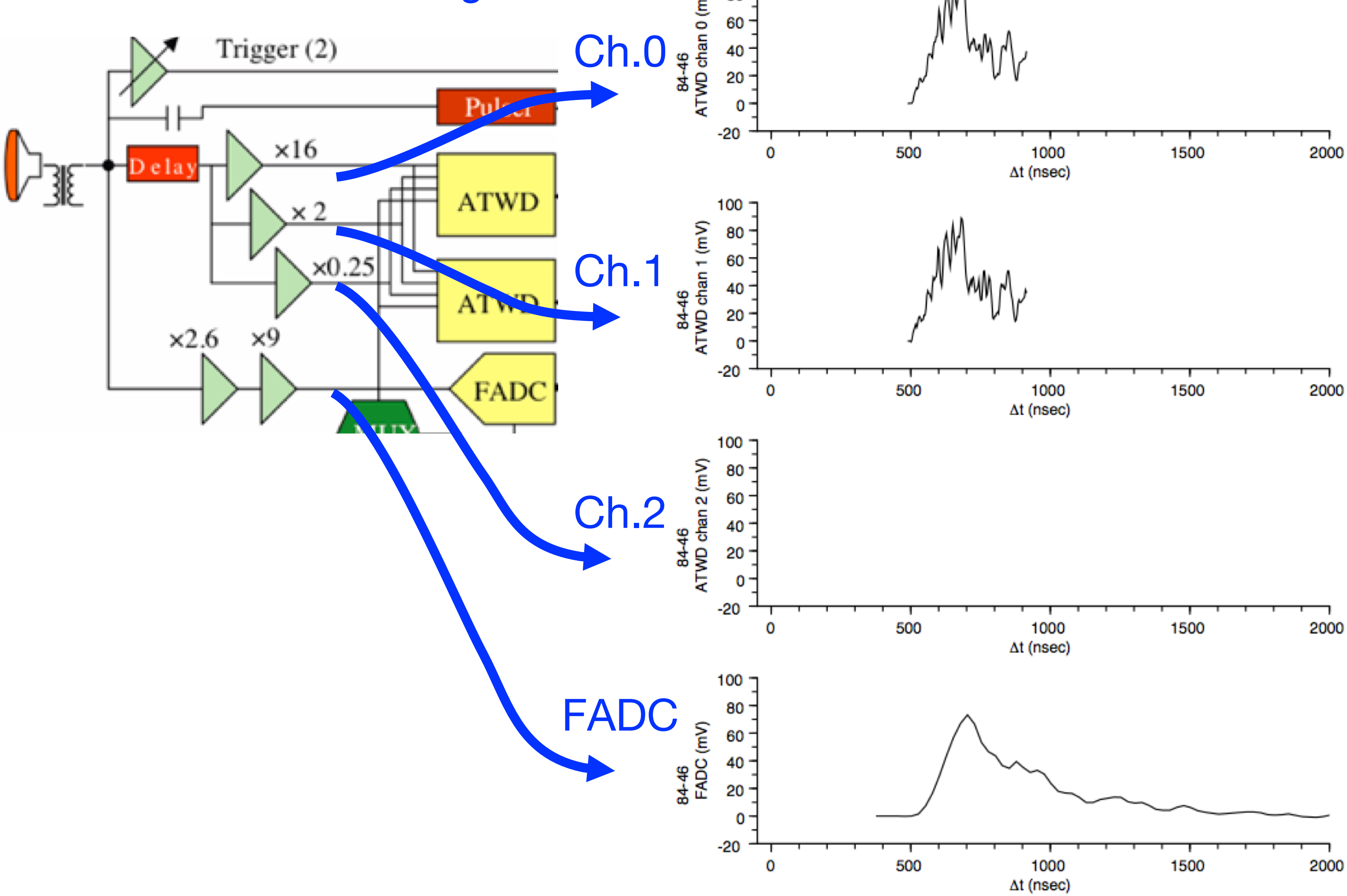
Waveform digitizers “ATWD” Ch. 0,1,2 and “FADC”

Ch.2 needed for large waveforms



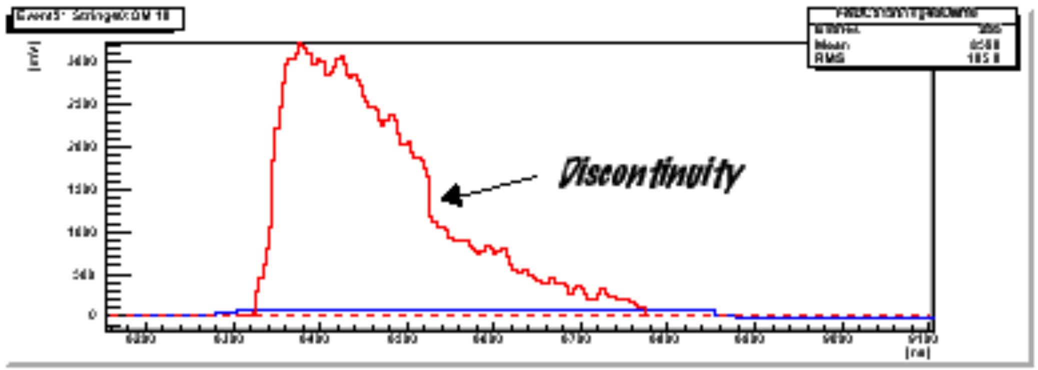
Waveform digitizers “ATWD” Ch. 0,1,2 and “FADC”

FADC needed for long waveforms



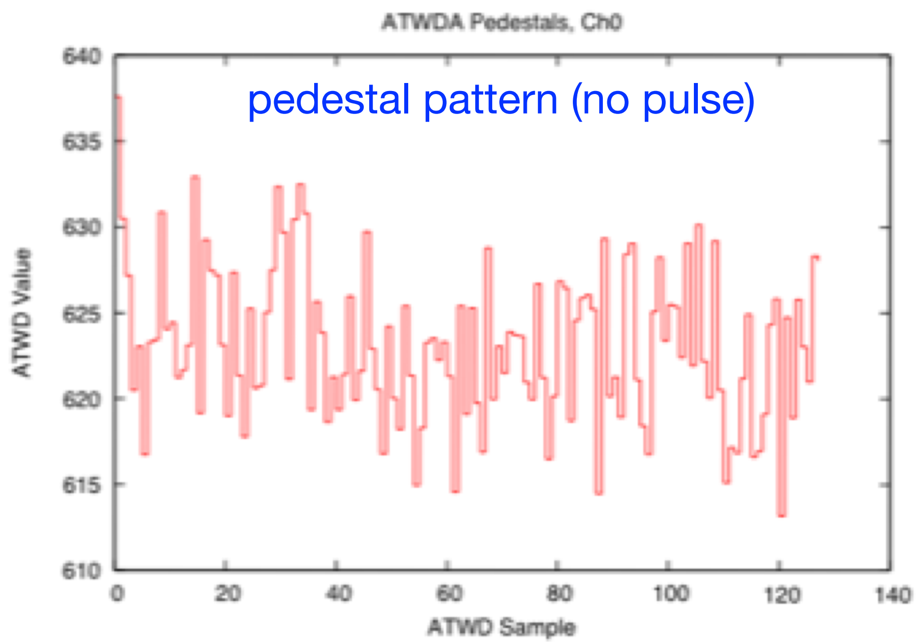
Why so many channels and digitizers?

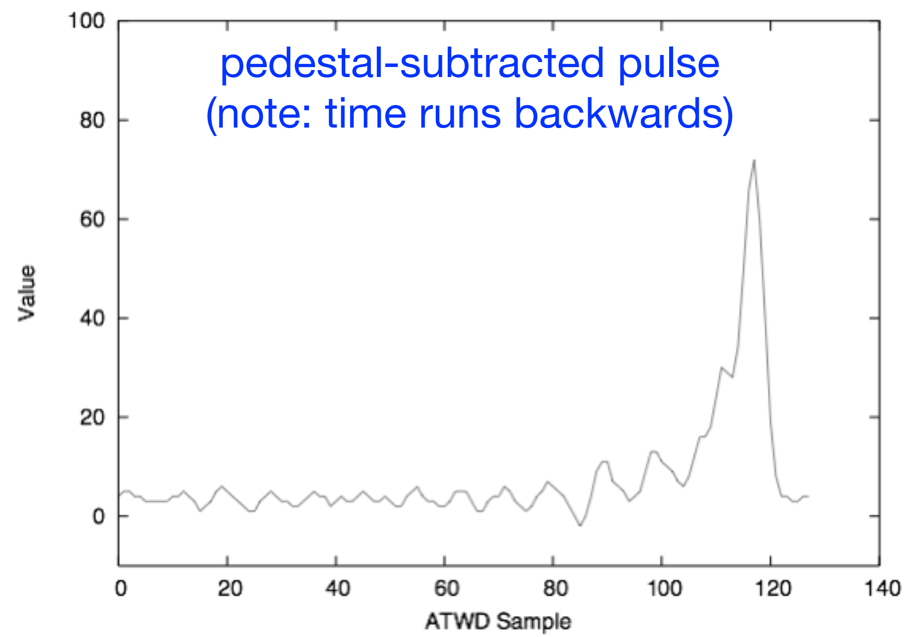
- Fast digitizers are power hungry, and the ATWD design was the alternative
  - When triggered, the ATWD quickly stores 128 samples of waveform, then digitizes these
  - During the digitization period, the ATWD is disabled, so a second one is provided to avoid losing additional hits ("ping-pong")
- The FADC is a slower digitizer to cover the case of longer waveforms
- Each channel had only 10 bit resolution so could not accommodate the dynamic range from small signals to large signals... thus needed ch.0/1/2
- But we pay a price in complexity and some funky problems when combining information from different gain channels



ATWD peculiarities

- Each ATWD has a “fingerprint” or pedestal pattern which much be subtracted from the waveform (happens automatically in the software)



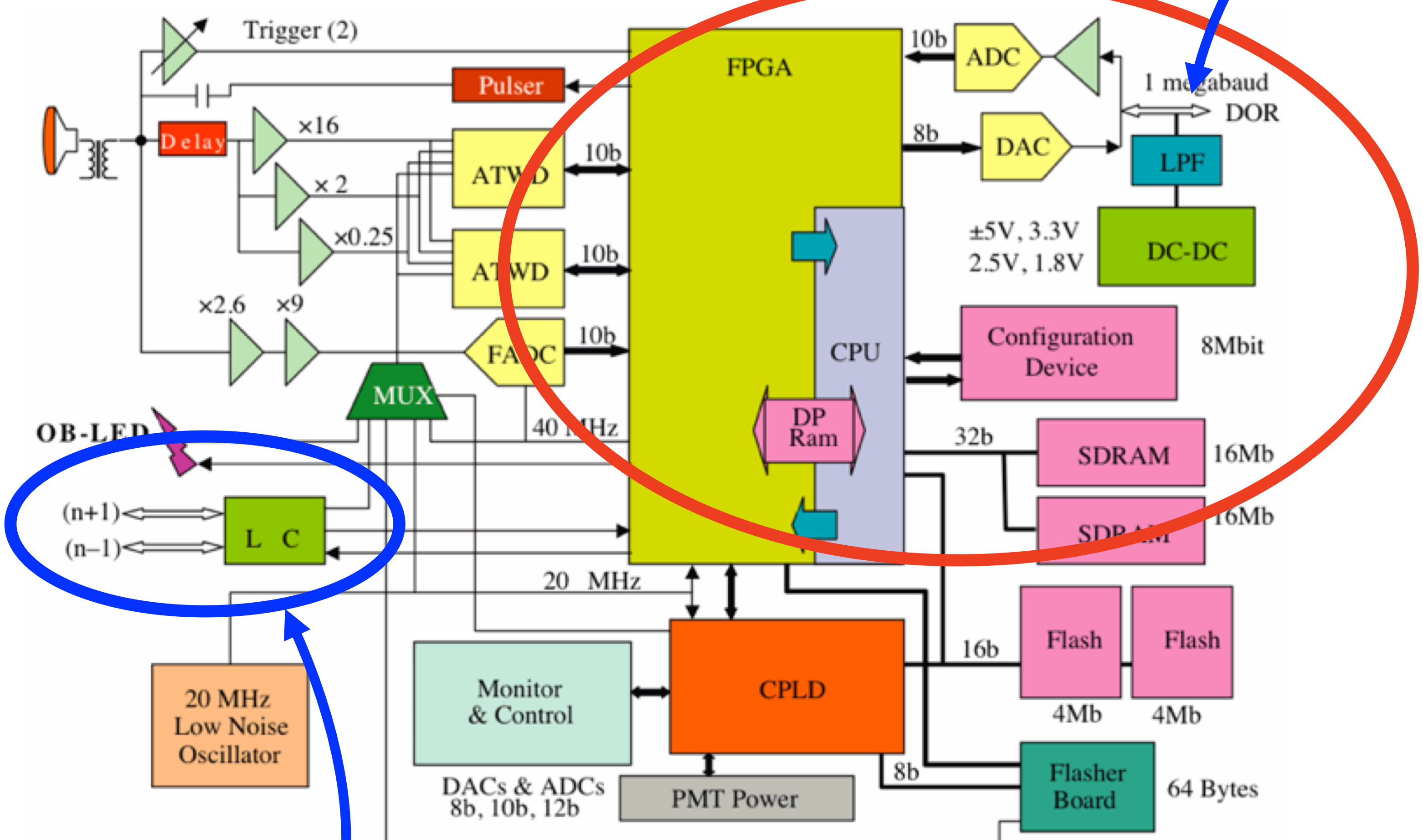


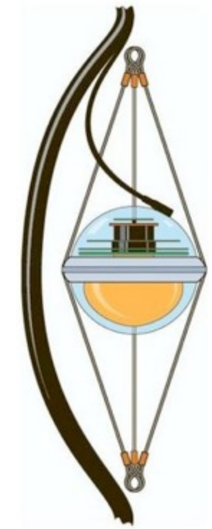
- Baseline voltage is very sensitive to DOM conditions; baselines are measured from previous runs and subtracted before pulses analyzed

- ATWD documentation:
  http://docushare.icecube.wisc.edu/docushare/dsweb/Get/Document-21613/atwd_manual.pdf
  http://glacier.lbl.gov/~thorsten/ATWD/

Sending waveforms to surface

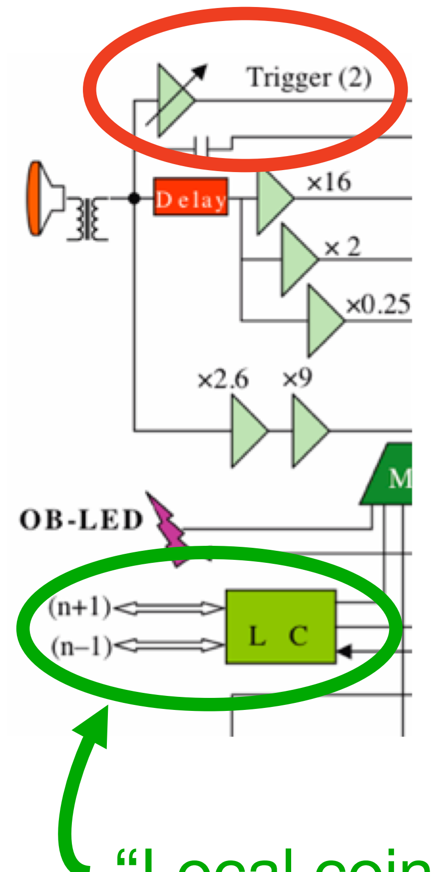
Connection to surface via main cable

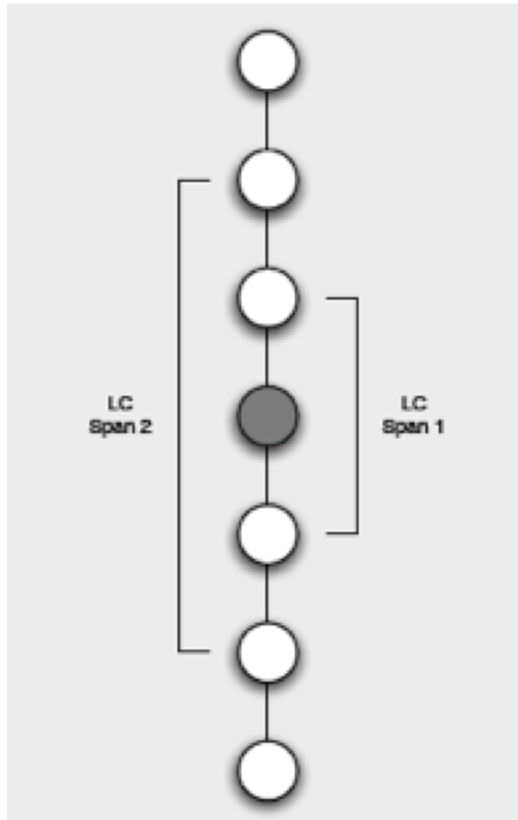


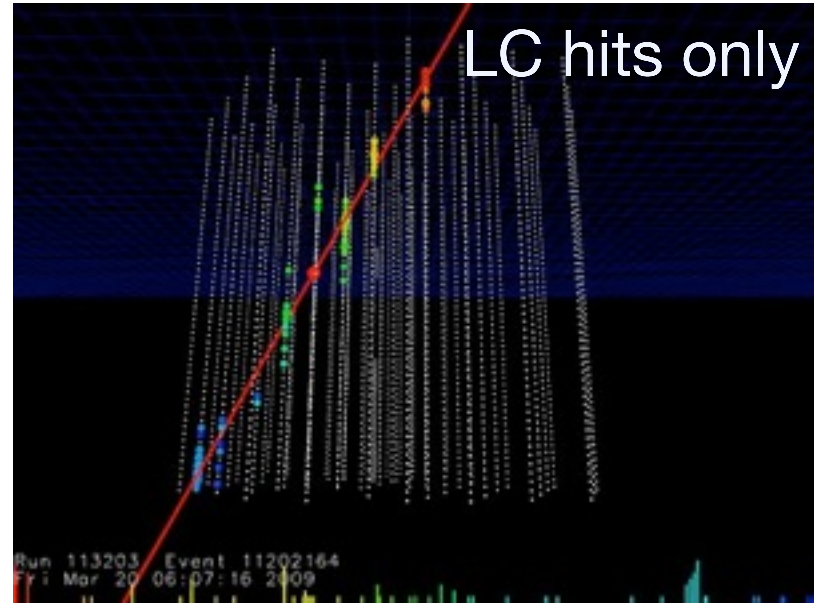


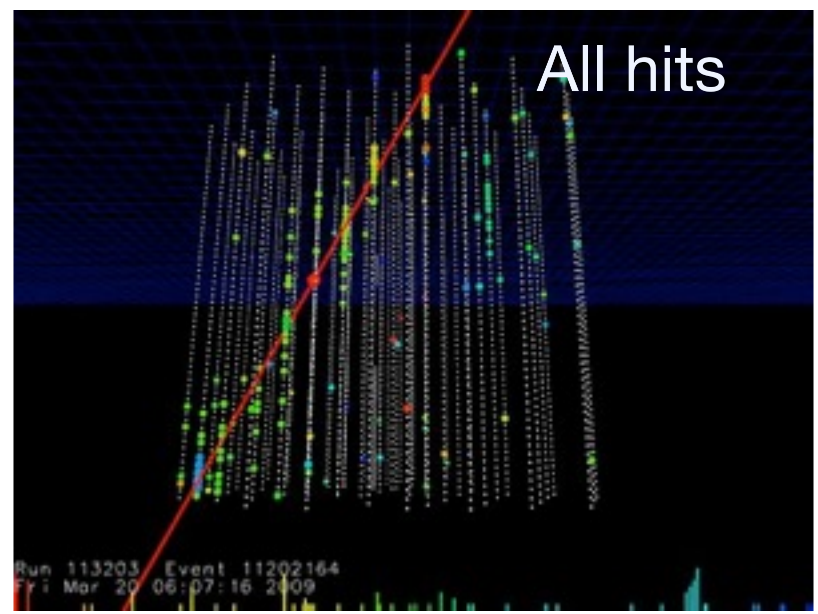
Connection to neighbor DOMs via main cable

Local Coincidence









"Local coincidence"

- *looks at whether a neighboring DOM also recorded an SPE*
- *1 μsec time window implemented in FPGA*
- *Many no-LC hits are from PMT dark noise, others are isolated signal photons*

Sending waveforms to surface

- Readouts *with* local coincidence “HLC Readouts”
  - Ch.0 + FADC
  - Ch.0 + Ch.1 + FADC
  - Ch.0 + Ch.1 + Ch.2 + FADC

Include enough channels to accommodate peak amplitude

Highly compressed ~150 bytes/record but all information is saved

- Readouts *without* local coincidence “SLC Readouts”

Only three samples of FADC are saved so time of SPE can be determined

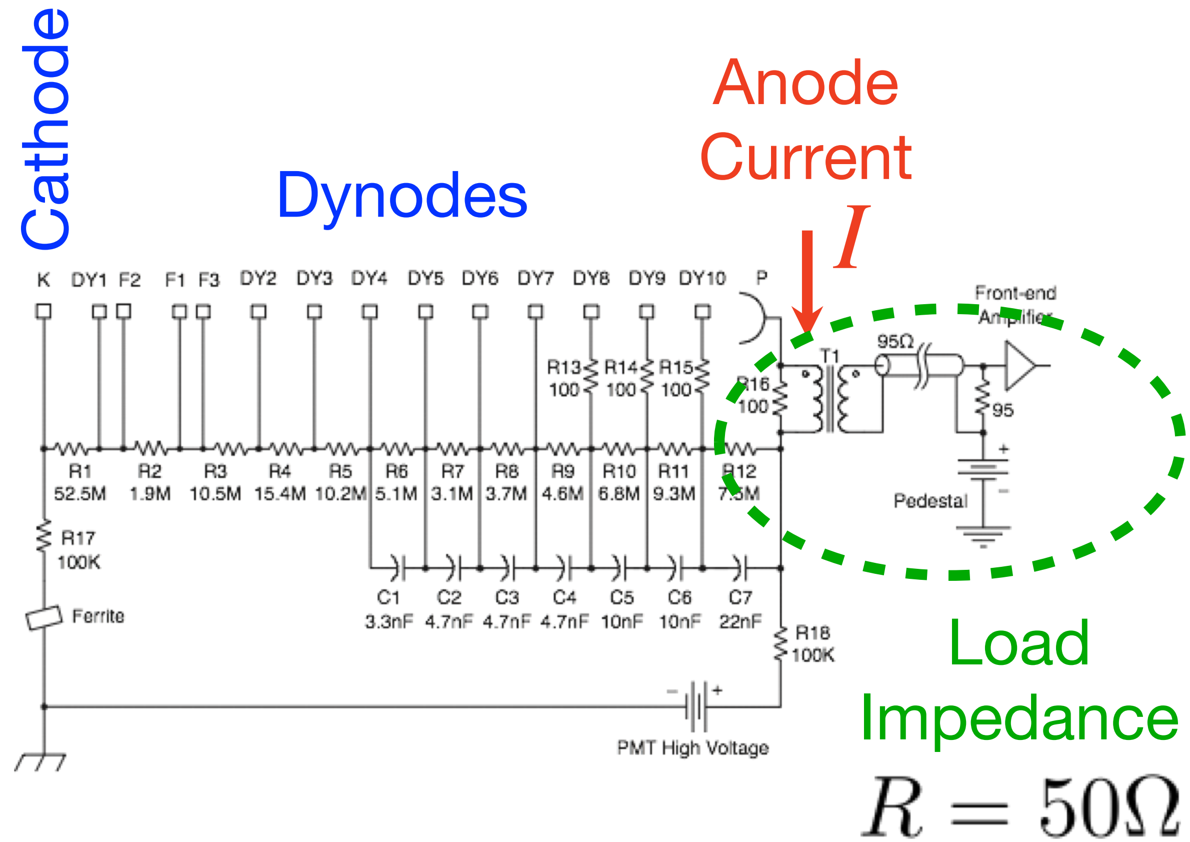
- All readouts are grouped into big chunks and transmitted to surface
- Must stay below 40kB/sec for each DOM, otherwise chunks of data get thrown away (“LBM overflows”)

Calibrations needed for interpreting waveforms

- Complex waveforms are just sums of individual SPE (single photoelectron) responses
- Integral of waveform is proportional to # photons
- Usually we give the integral as total charge

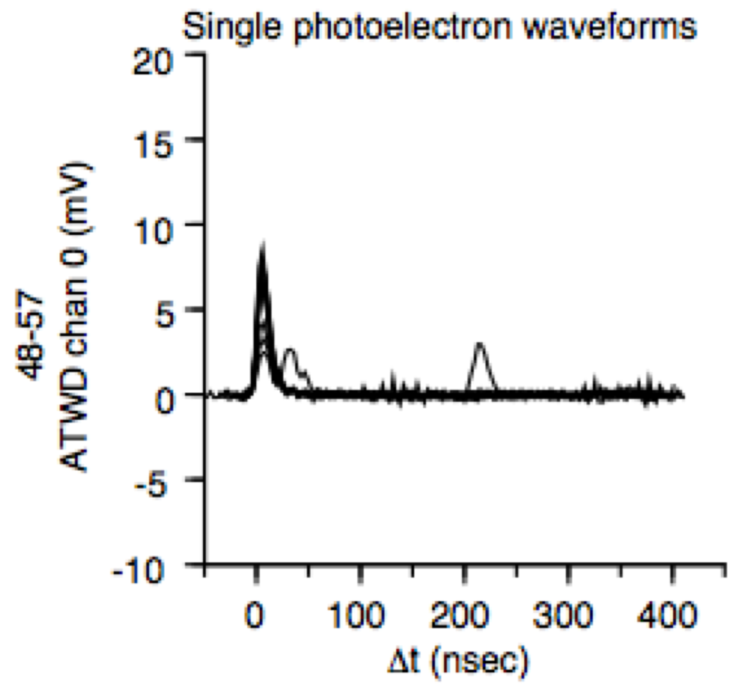
$$Q = \int I \, \mathrm{dt} = \frac{1}{R} \int V \, \mathrm{dt}$$

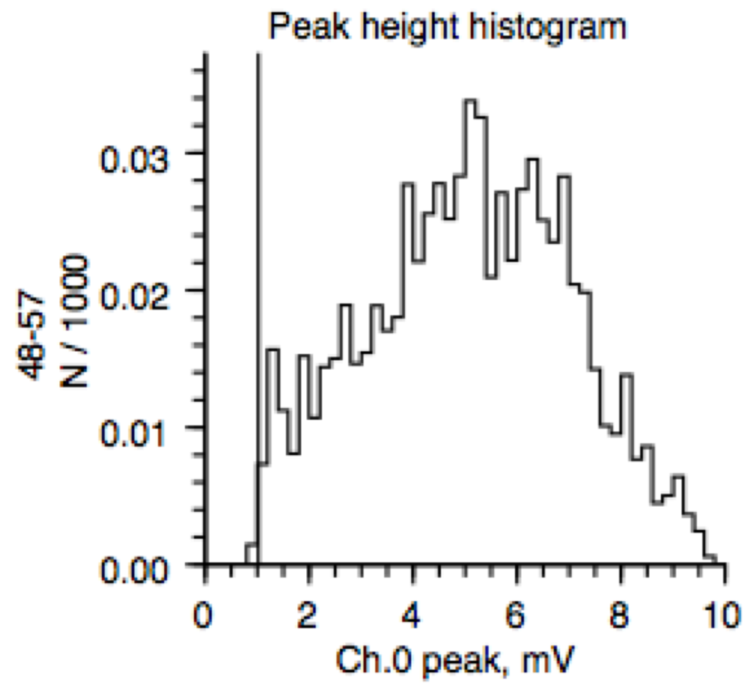
- Units can be pC, or “SPE” where “SPE” = Gain x e
  = 10^7 e
  = 1.6 pC



Reminder of PMT response for single photons

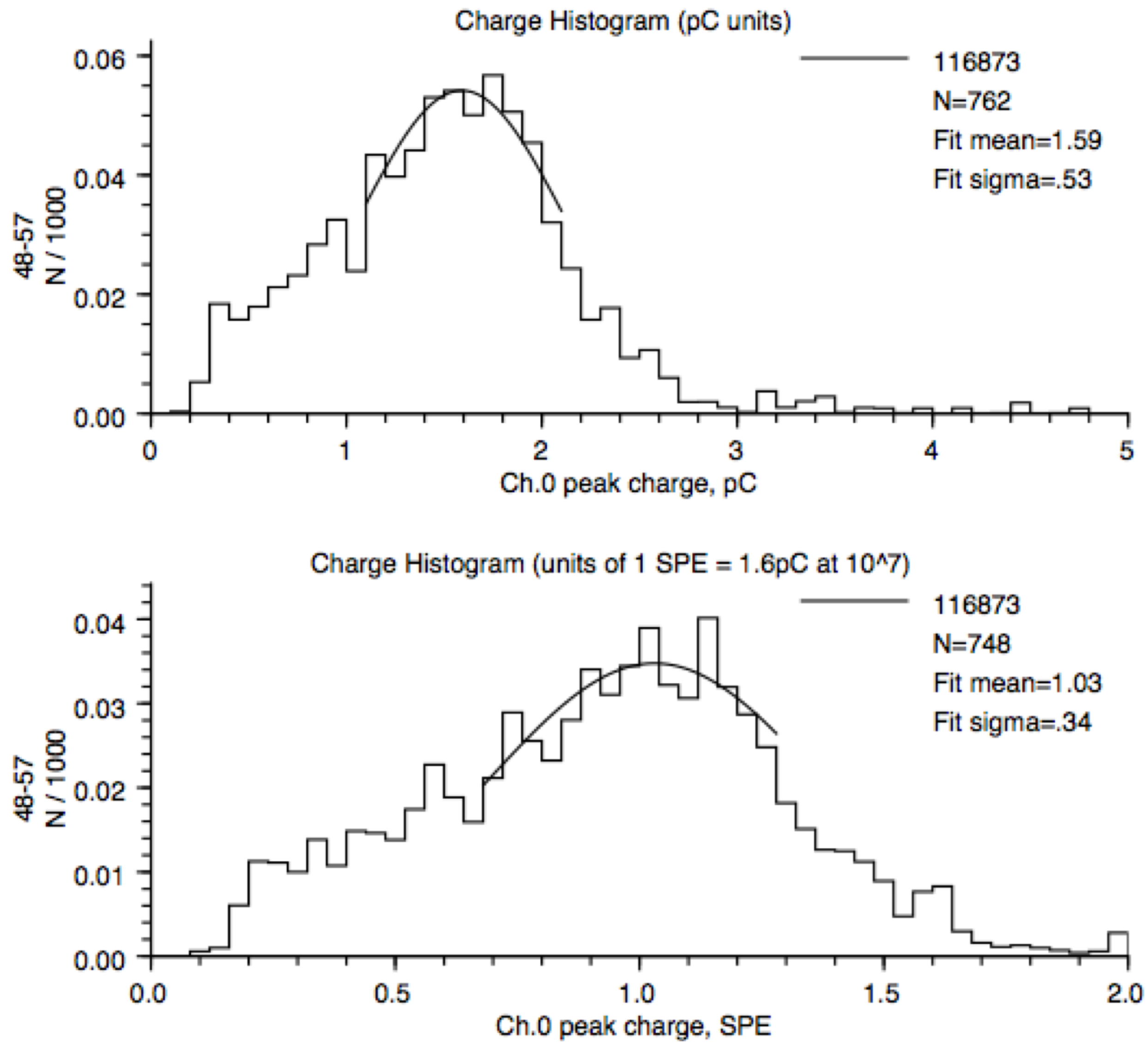
- Pulse heights vary ±30%, with tail on low side





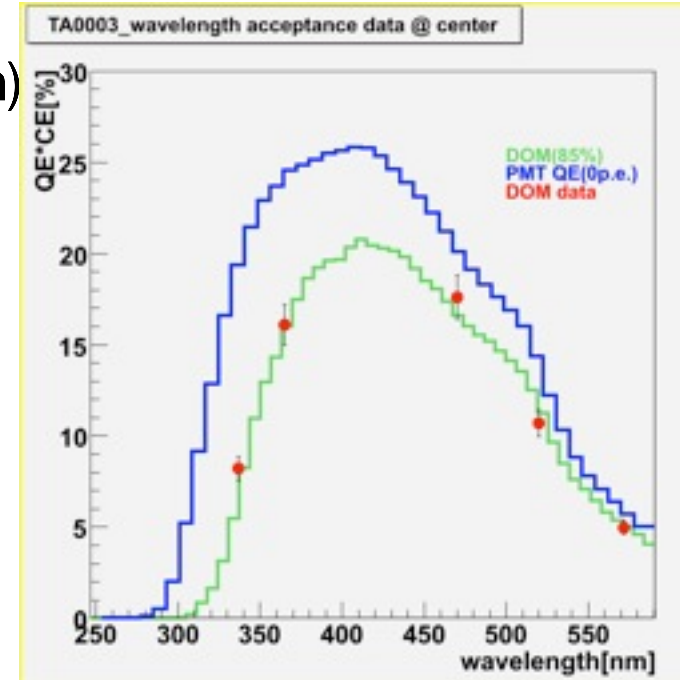
Single photoelectron charge

- Distribution similar to peak voltage, but area (charge) more convenient
- PMT high voltages are tuned so SPEs give charge of 1.6pC (Gain 10^7)
- Single photons are our calibration source!

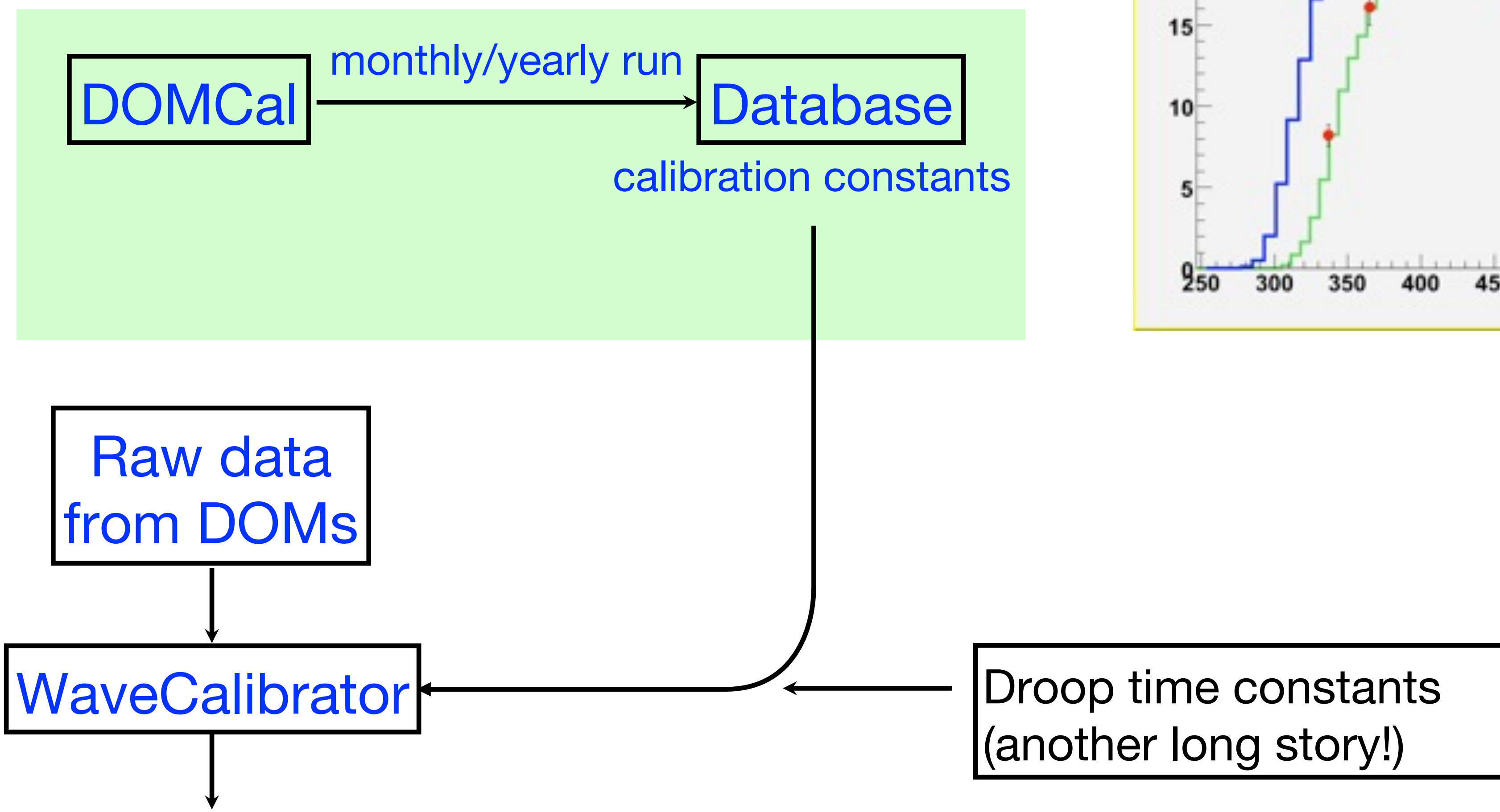


Calibration inputs for counting photons

- DOM sensitivity (prob. that photon yields photoelectron)
  --- Depends on angle, currently known to ±10%



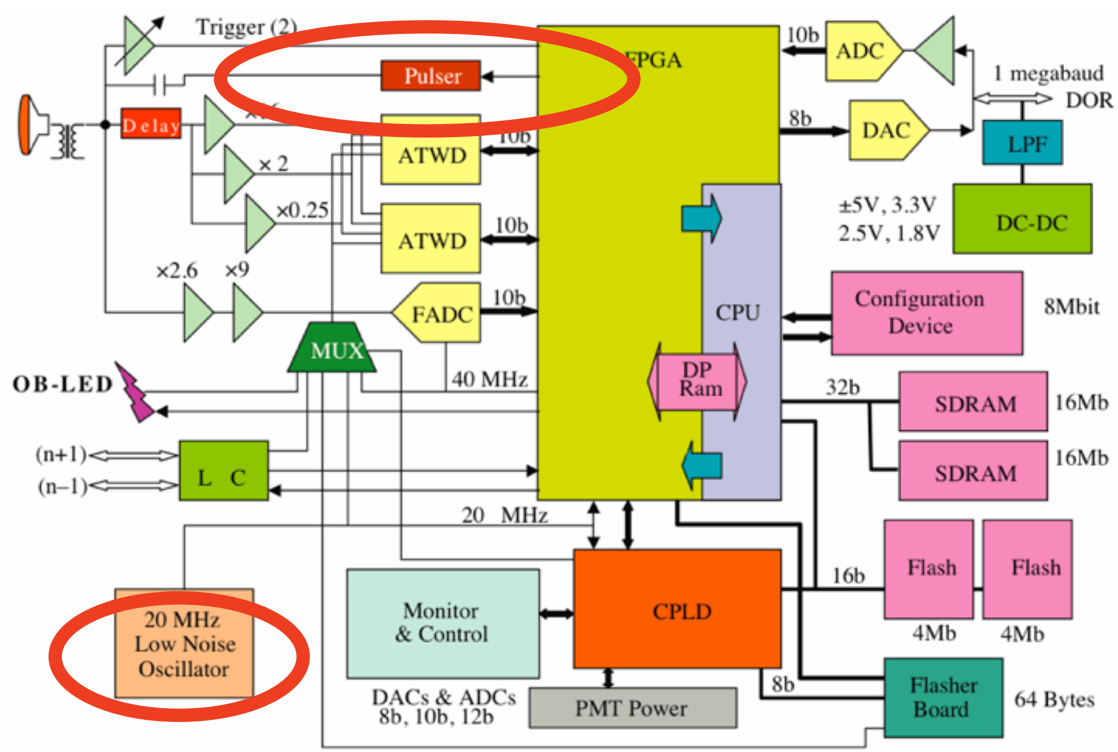
- Calibration of electronic response for SPEs

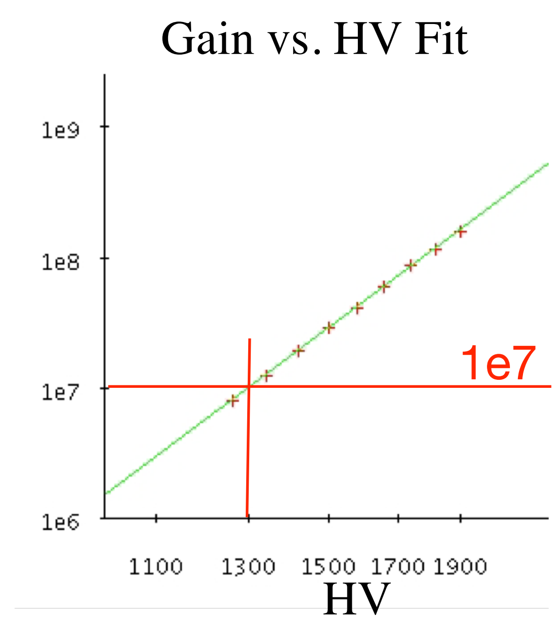


- Waveform analysis software

DOMCal

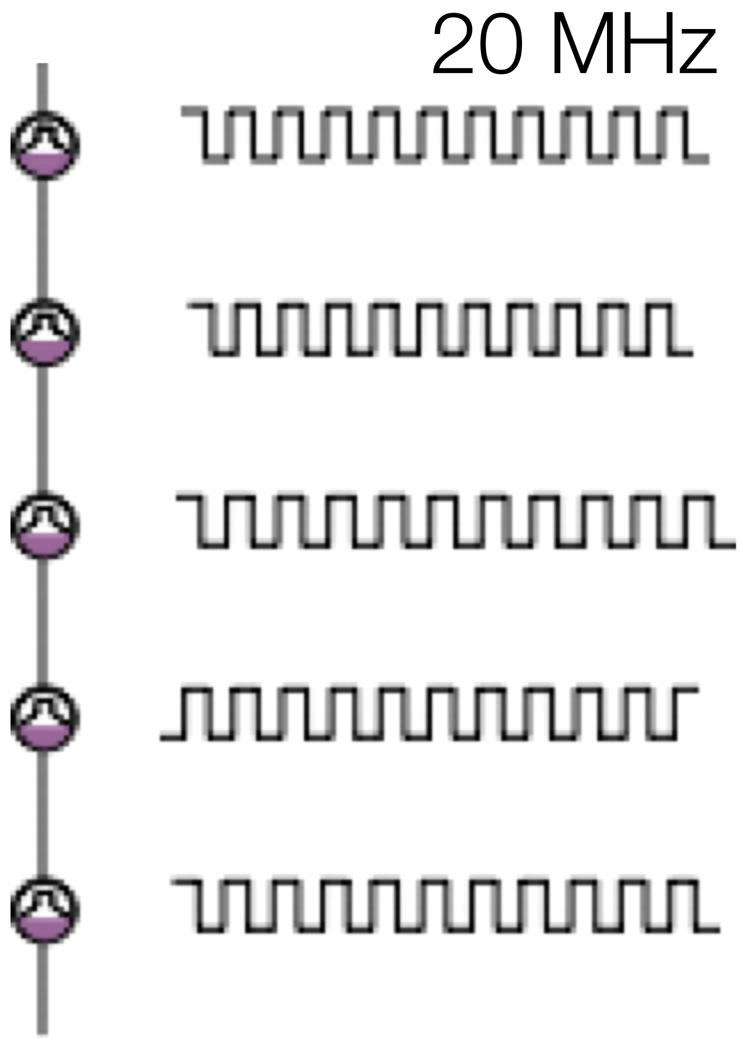
- Written & maintained by Jim Braun, John Kelley, Chris Weaver
- Runs on the DOM mainboard CPU
- Measures calibration constants for converting raw waveform data to millivolts vs. time in nsec





- Measures PMT Gain vs High Voltage, so we can set all PMTs at similar gain (generally 10^7)

Time Synchronization



- Every DOM has its own reference clock for recording hit times

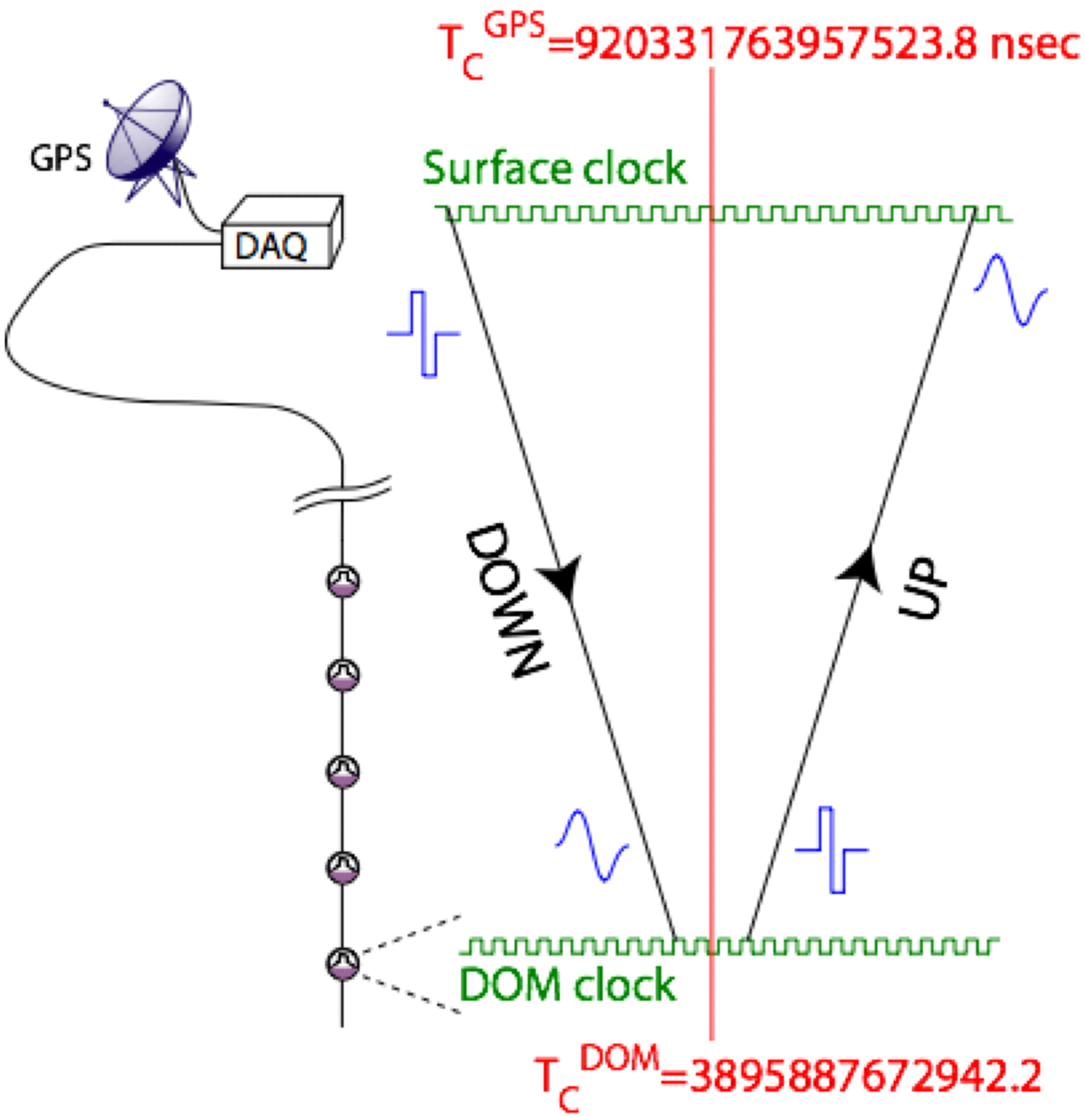
- Very low drift

$$\frac{\Delta f}{f} \sim 10^{-10} \quad \text{over 5 secs}$$

but still need synchronization for nsec precision

Time Synchronization - RAPCal

Reciprocal
Active
Pulsing



- Pulses degraded over 3km cable but reciprocal so errors cancel
- Don't need to know cable delays
- Automatic process every second

Surface DAQ can correct hit times before recording

$$T^{GPS} = k\, T^{DOM} + T^{offset}$$

rms of ~2 ns