DOMs and the DAQ Demystified
Part I: DOMs

John Kelley
UW-Madison

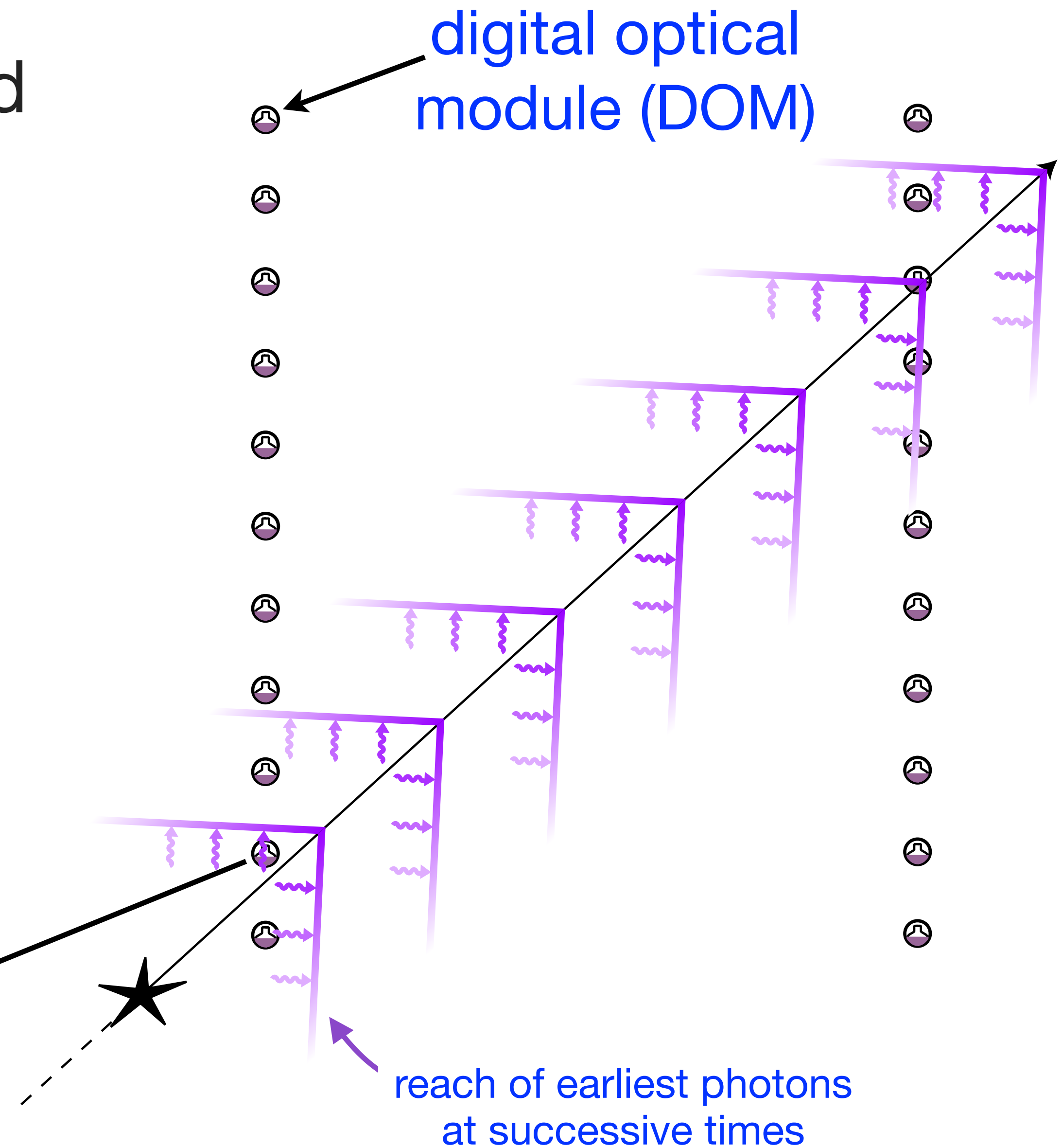
IceCube Bootcamp, 2015-06-09

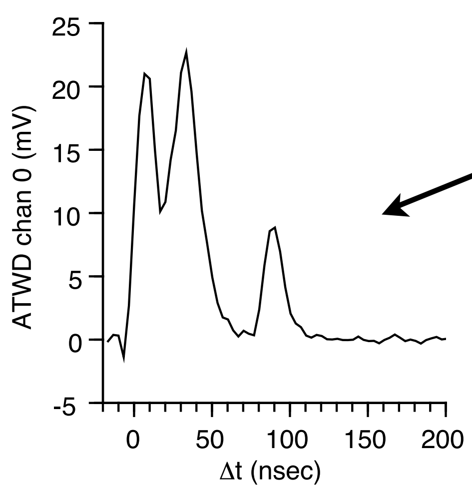
with thanks to Chris Wendt

$\nu_\mu \rightarrow \mu$ Detection

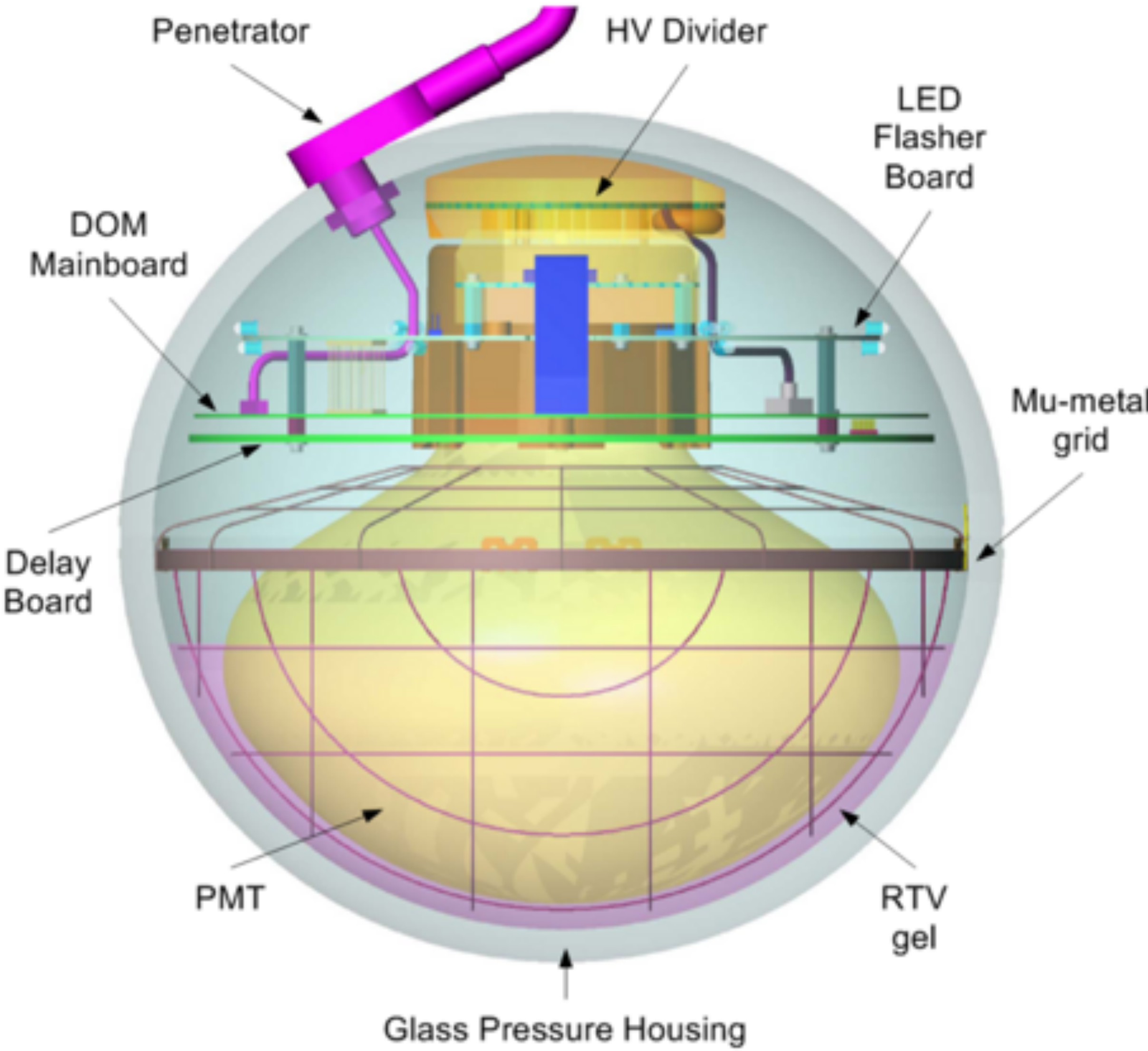
- Light is mostly emitted in small bursts along muon track

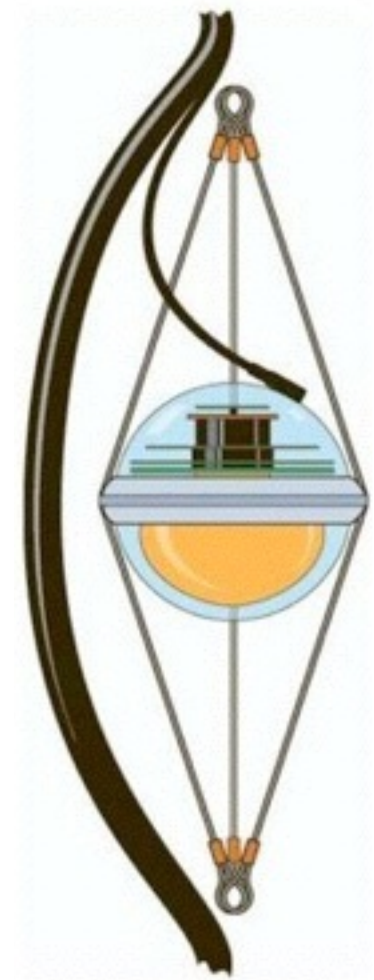
- Photon arrival times, and how many there are, tell us the direction and the energy of the muon





What's in a DOM?

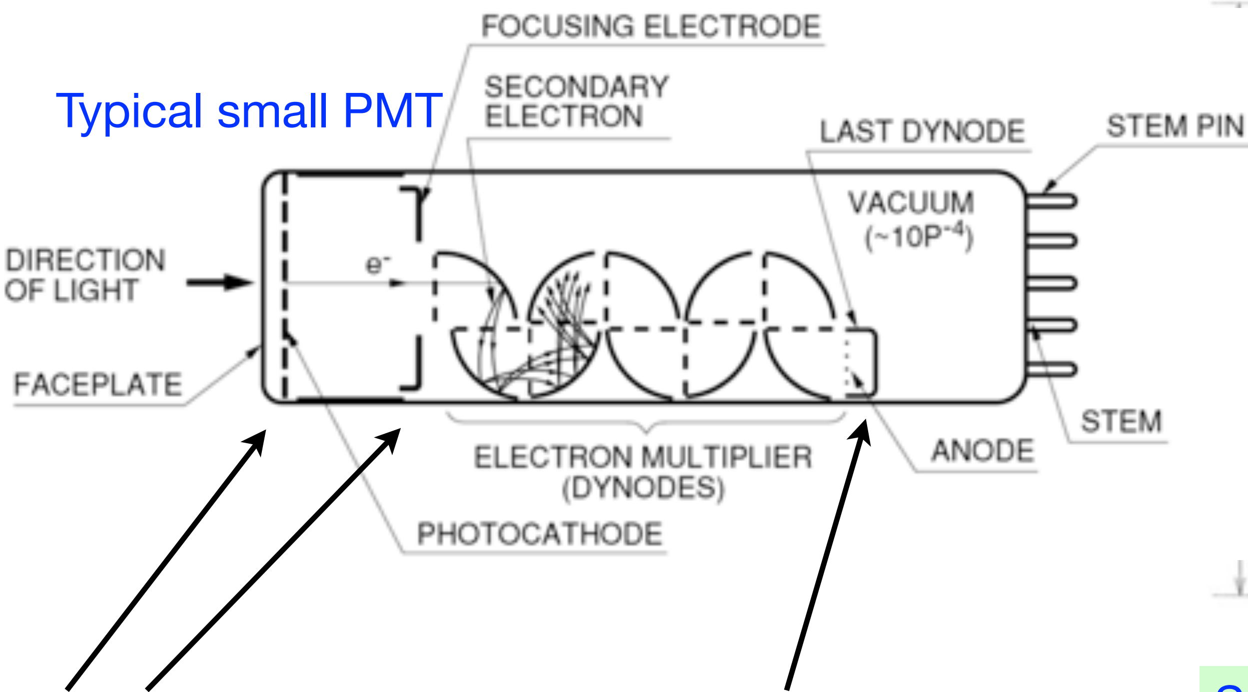


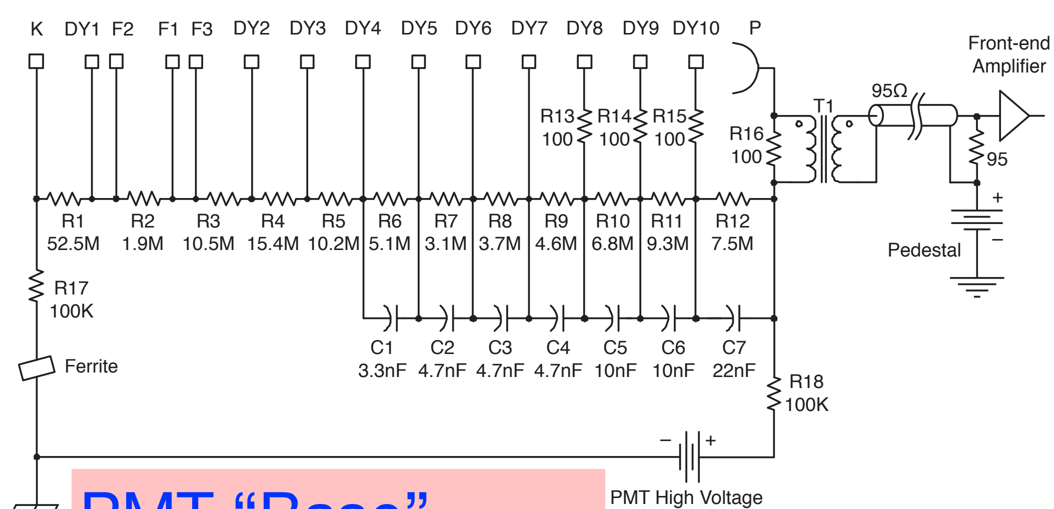


Cable: many twisted pairs, each pair carries power & communications for 2 DOMs

Photomultiplier Tube (PMT)

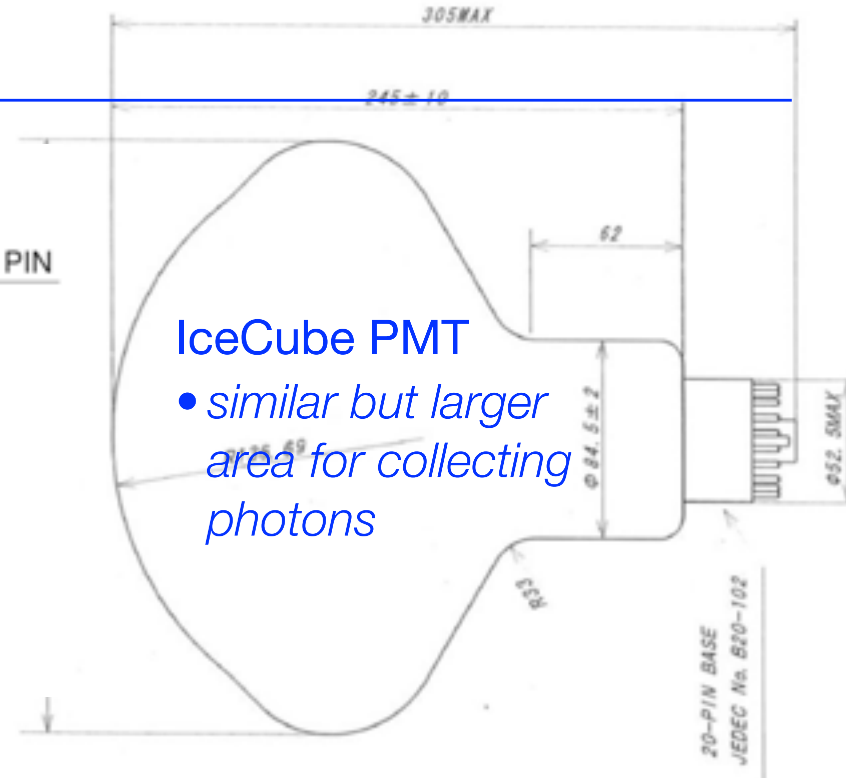
Typical small PMT





PMT "Base"
= Voltage Divider

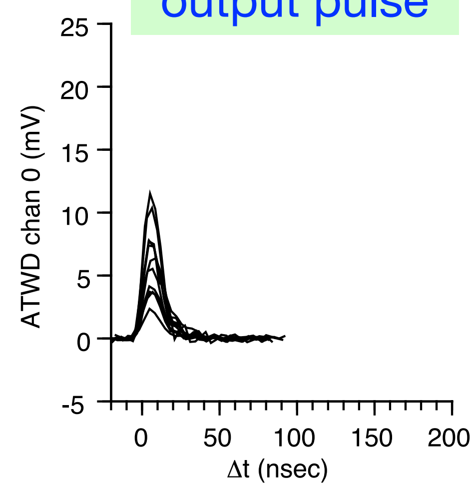
~1500 volts



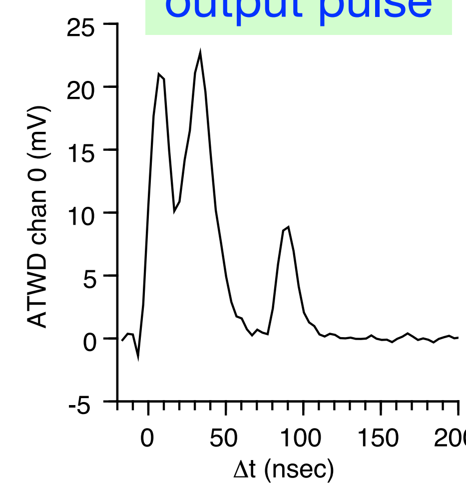
IceCube PMT

- *similar but larger area for collecting photons*

Single photon output pulse

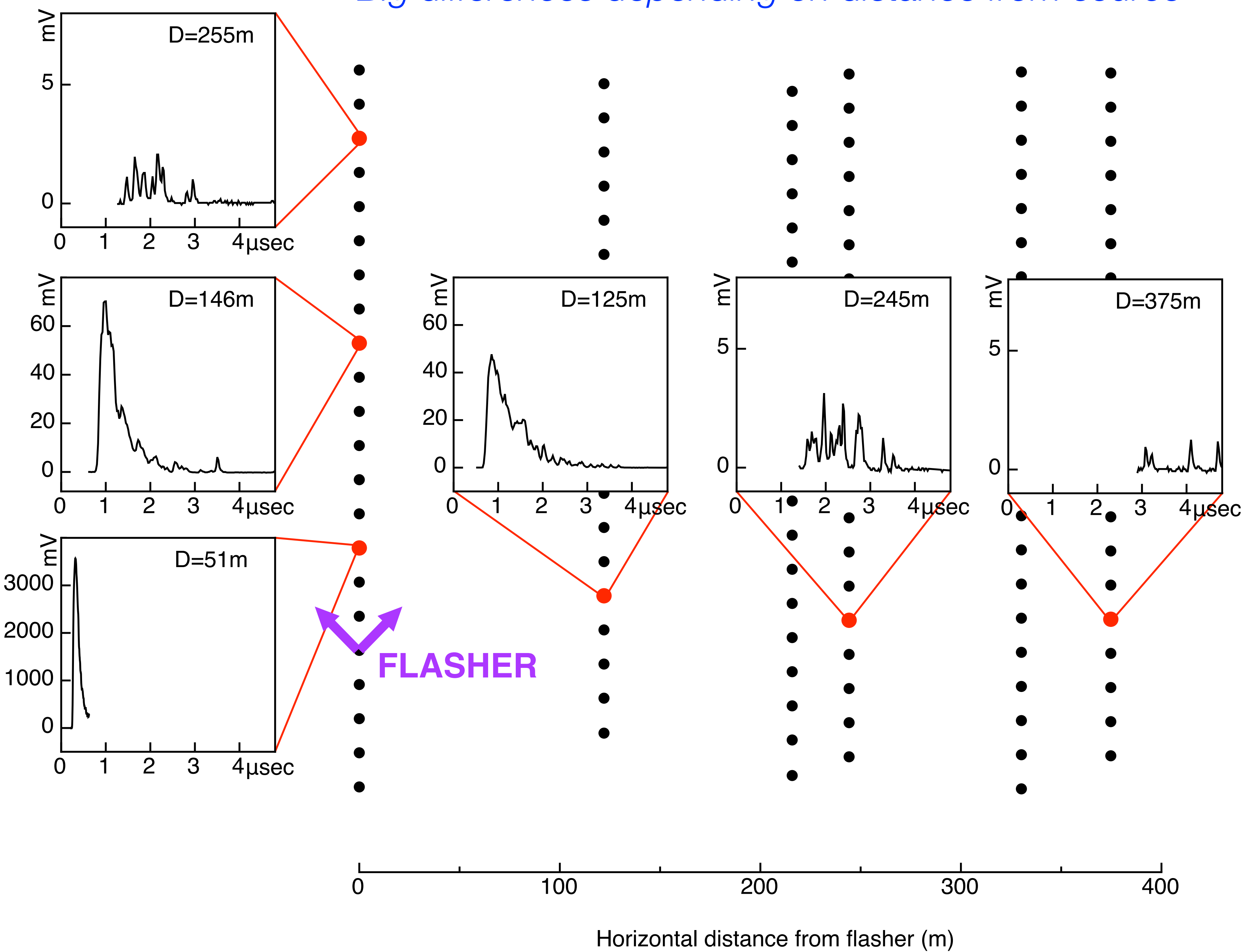


Multi-photon output pulse



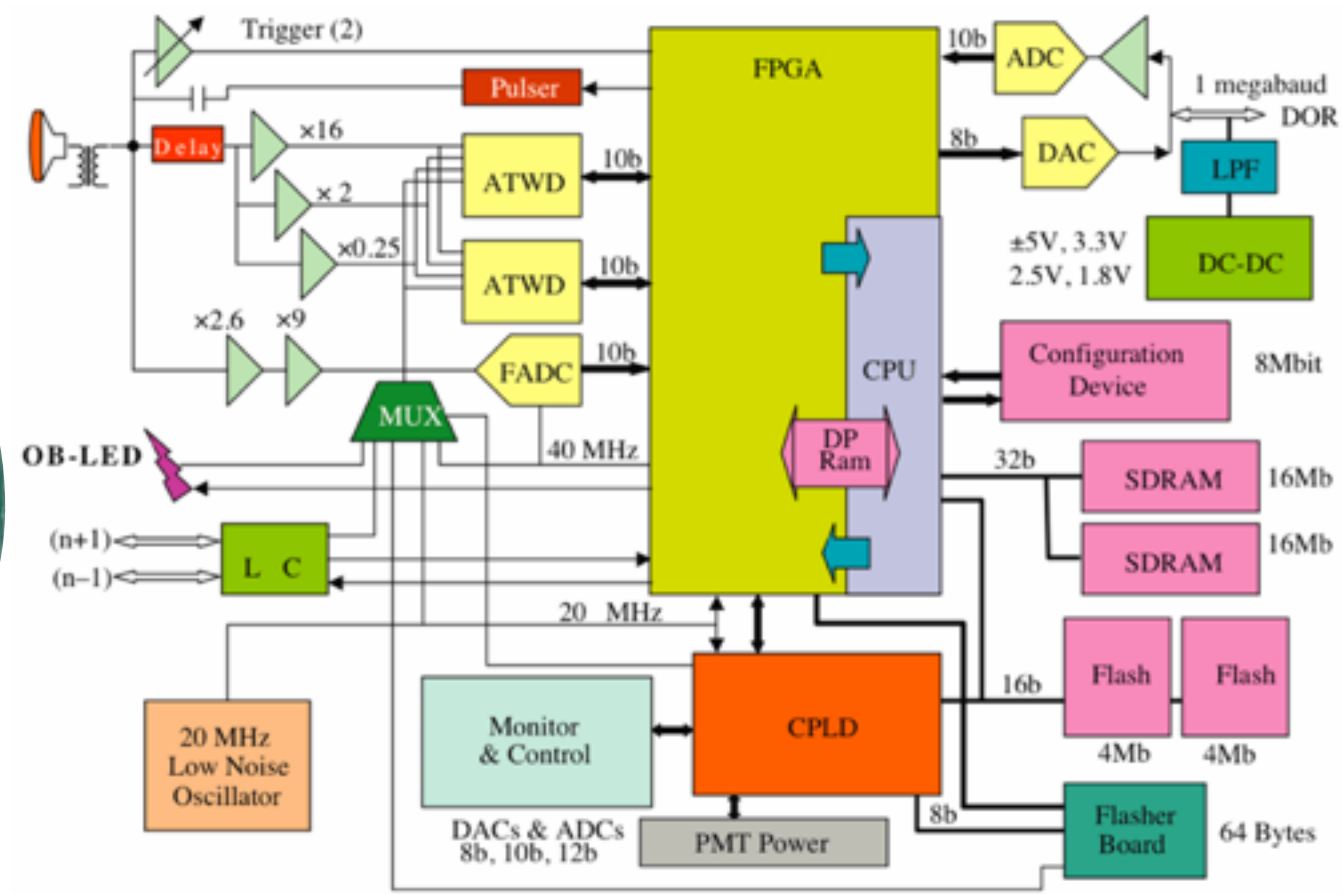
DOM signals resulting from localized light flash

- *Big differences depending on distance from source*



DOM Main Board

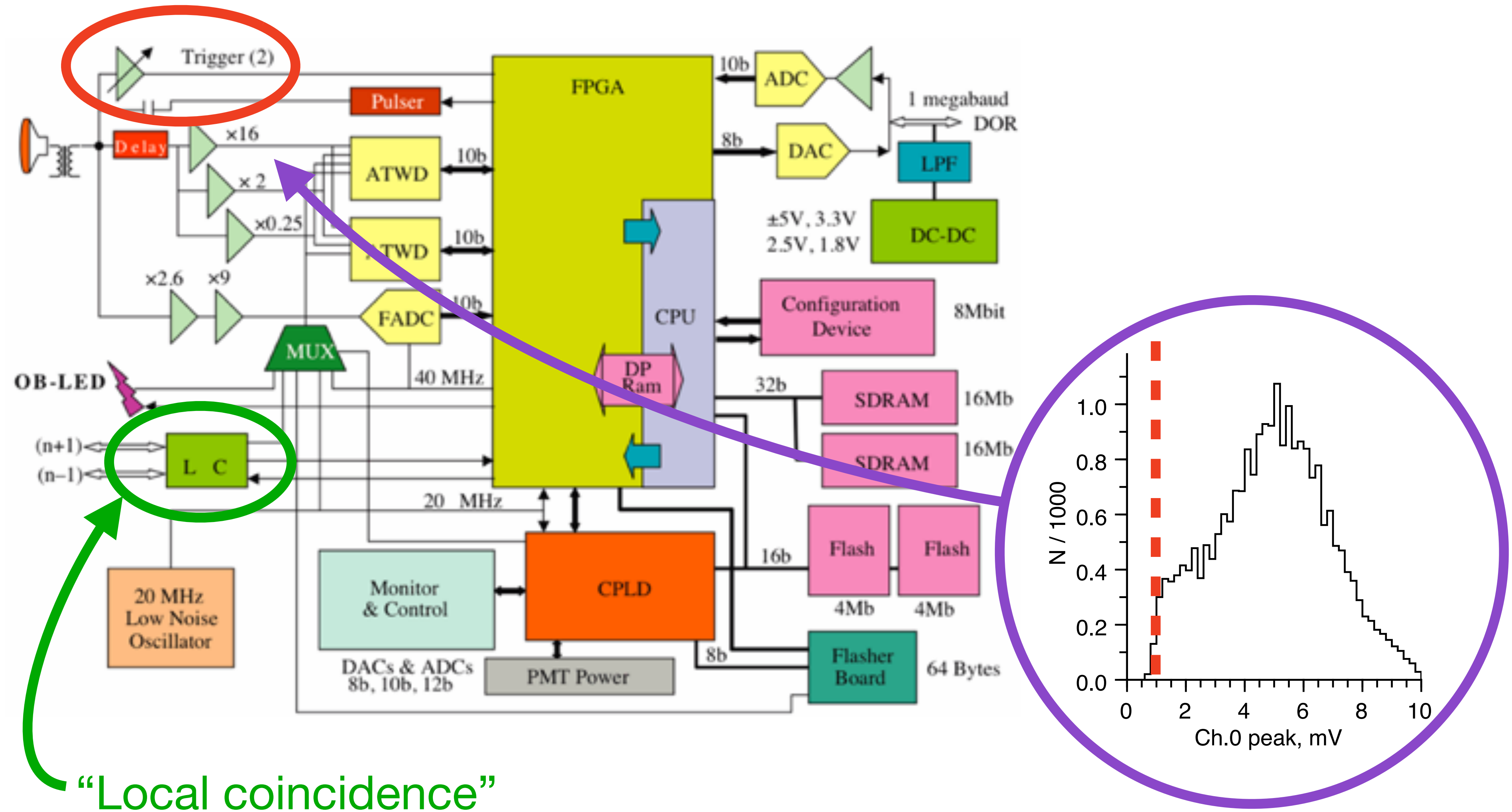
Contains waveform digitizers, on-board computer, communications circuits, HV & flasher control, etc.



"The IceCube Data Acquisition Subsystem: Signal Capture, Digitization, and Time-Stamping"
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

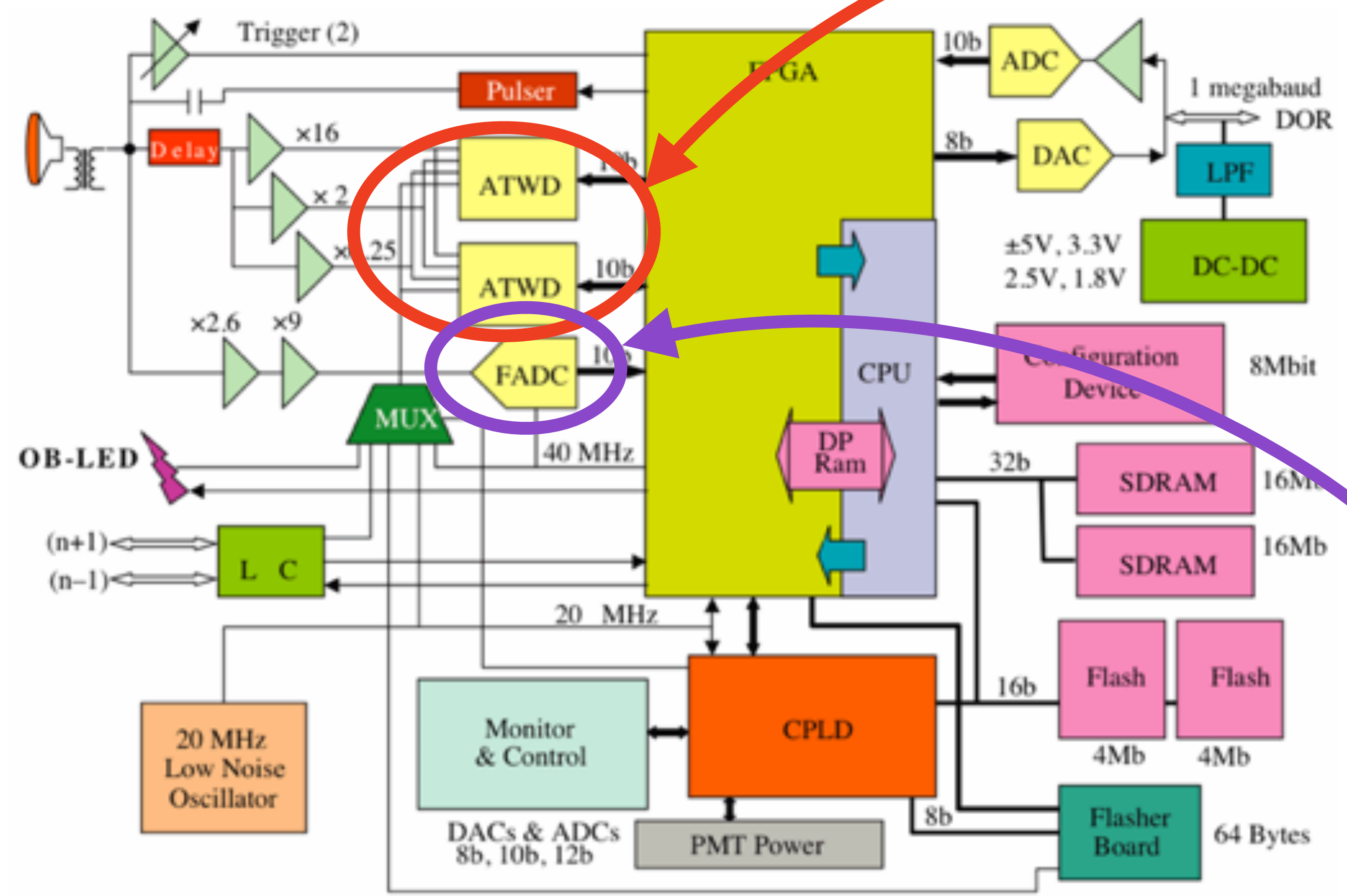
Actually single photoelectrons, “SPEs”



“Local coincidence”

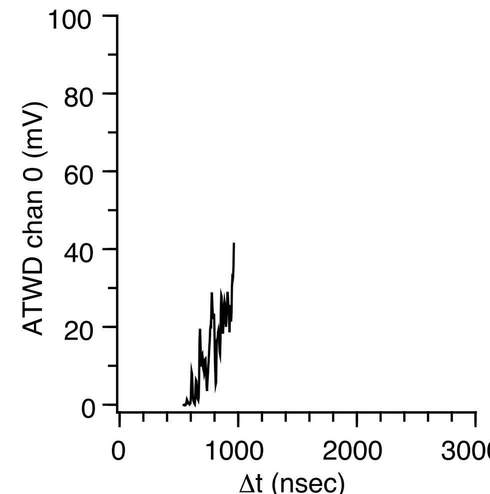
- *looks at whether a nearby DOM also recorded an SPE*

Waveform recorders (digitizers)



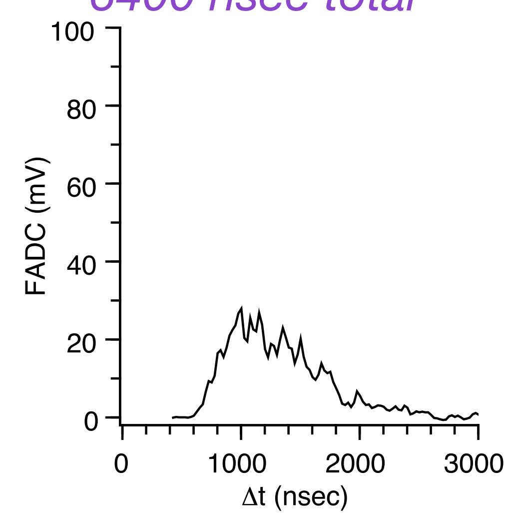
ATWD (2 in parallel)

- 3.3 nsec samples
- 427 nsec total



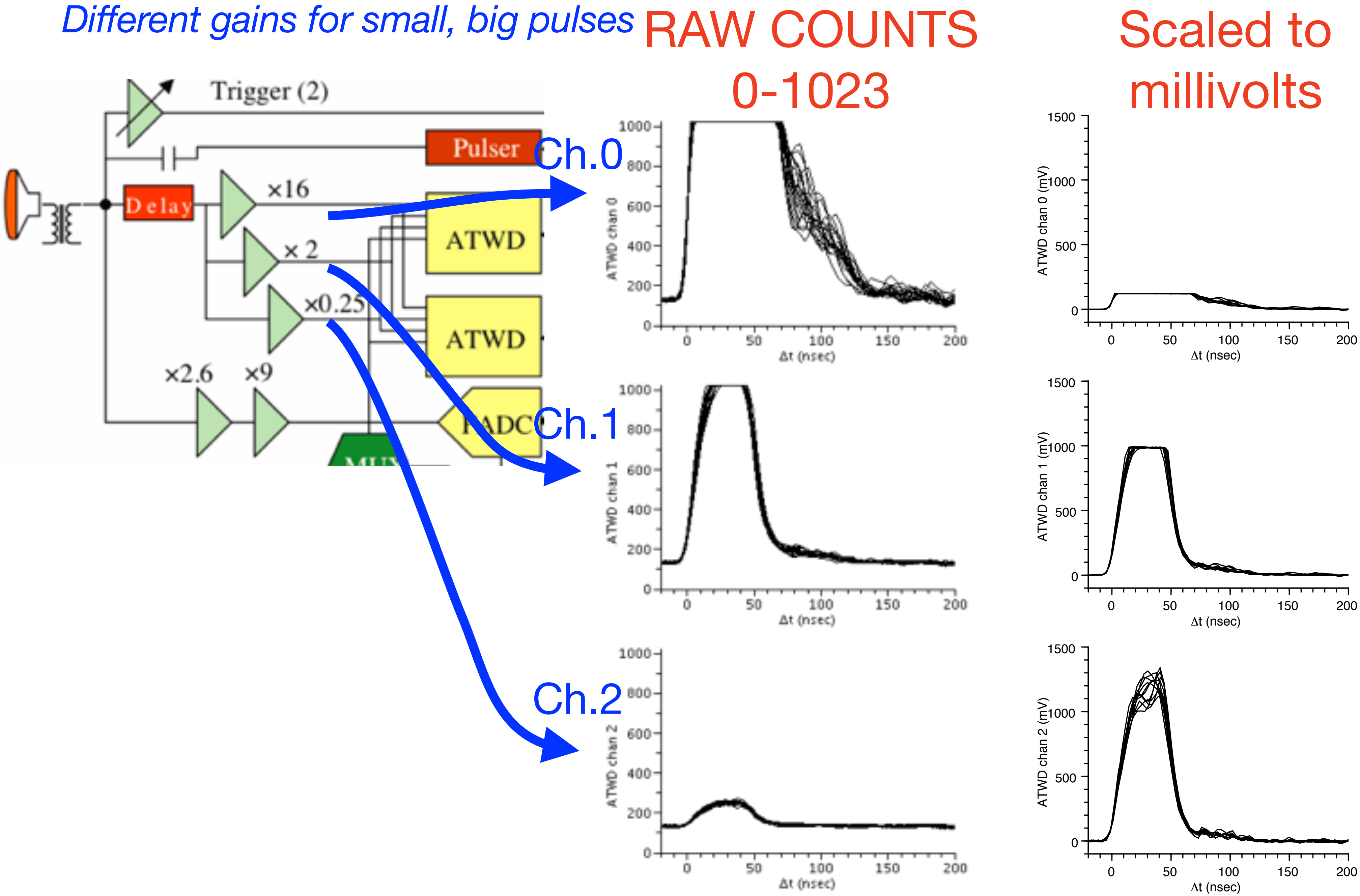
FADC

- 25 nsec samples
- 6400 nsec total



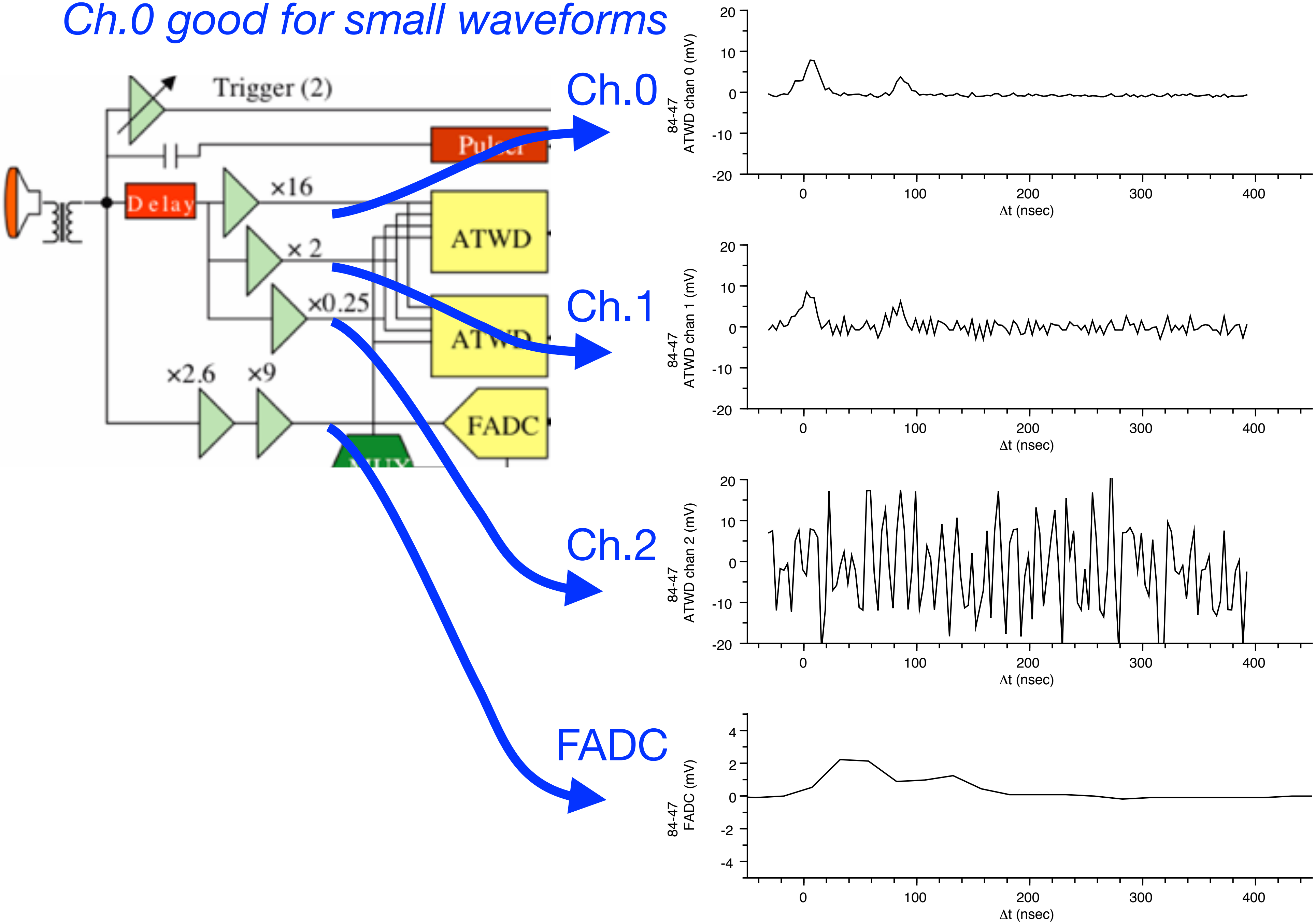
Waveform digitizers “ATWD” Channel 0,1,2

Different gains for small, big pulses



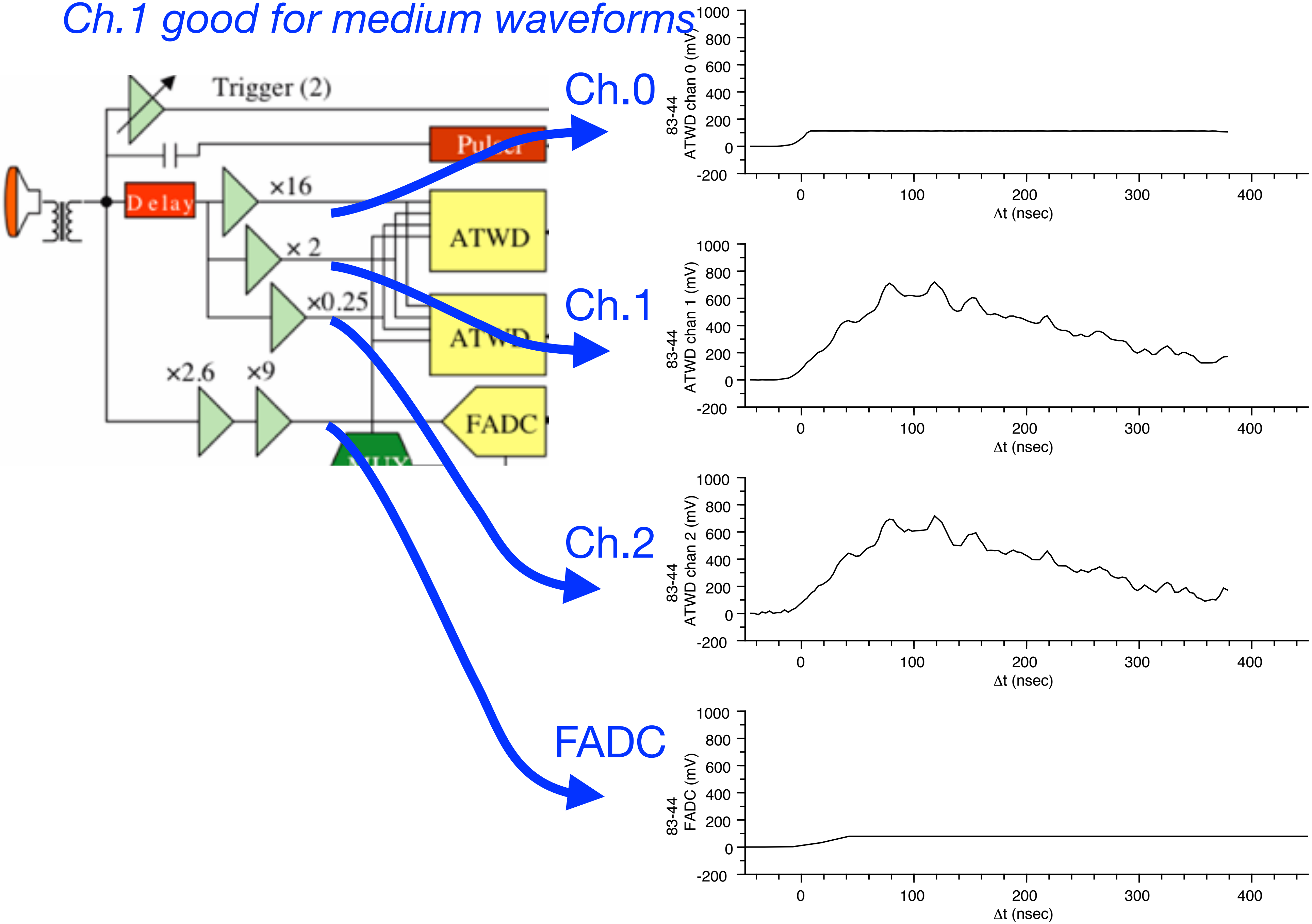
Waveform digitizers “ATWD” Ch. 0,1,2 and “FADC”

Ch.0 good for small waveforms



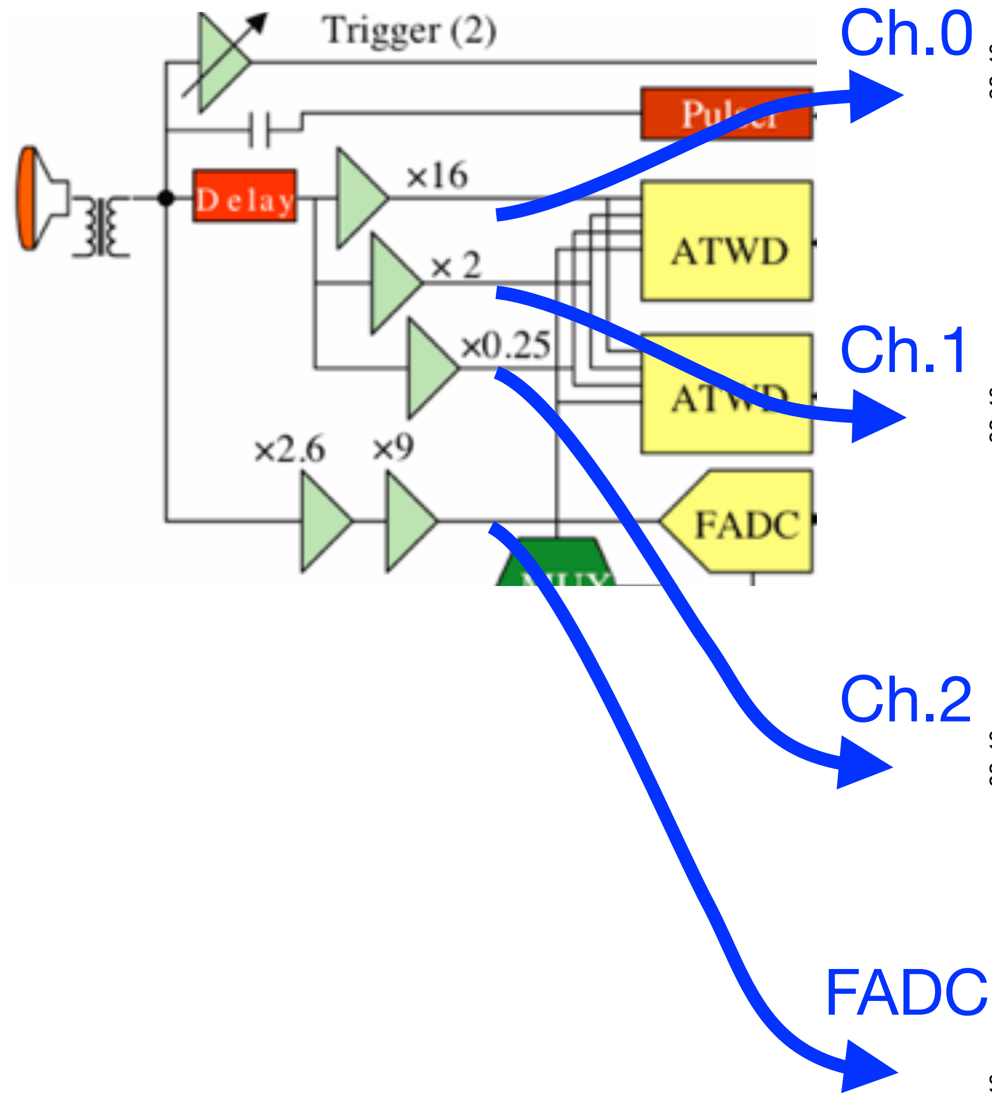
Waveform digitizers “ATWD” Ch. 0,1,2 and “FADC”

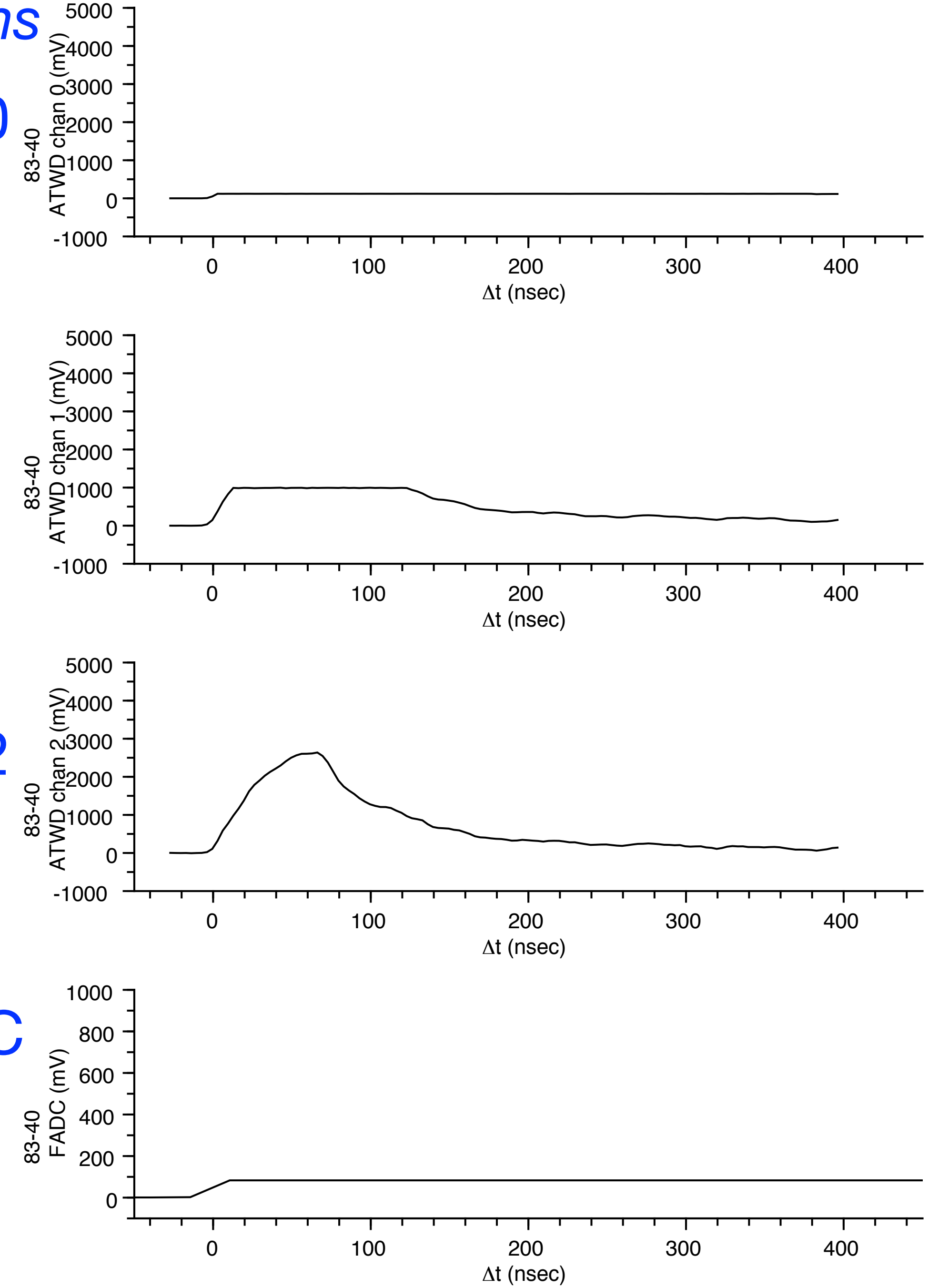
Ch.1 good for medium waveforms



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

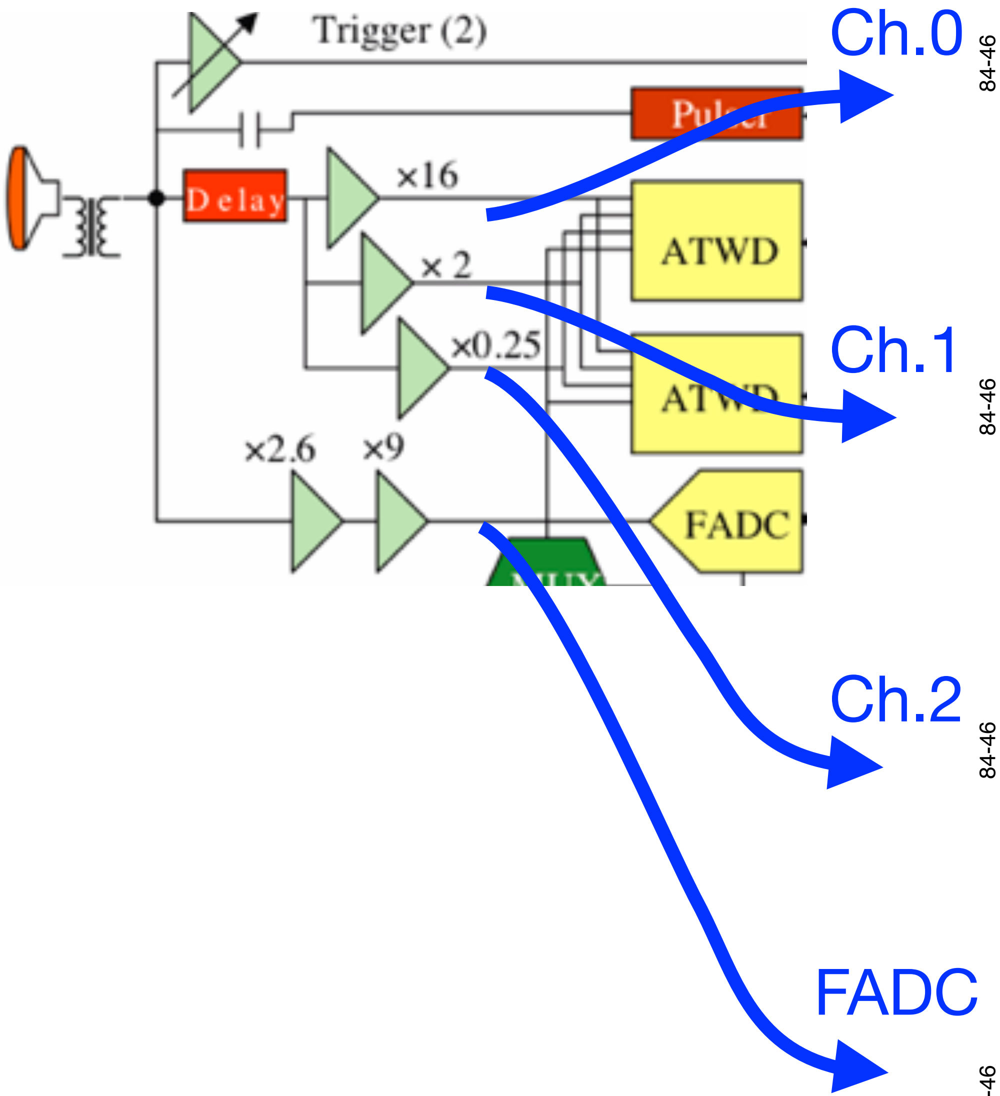
Ch.2 needed for large waveforms

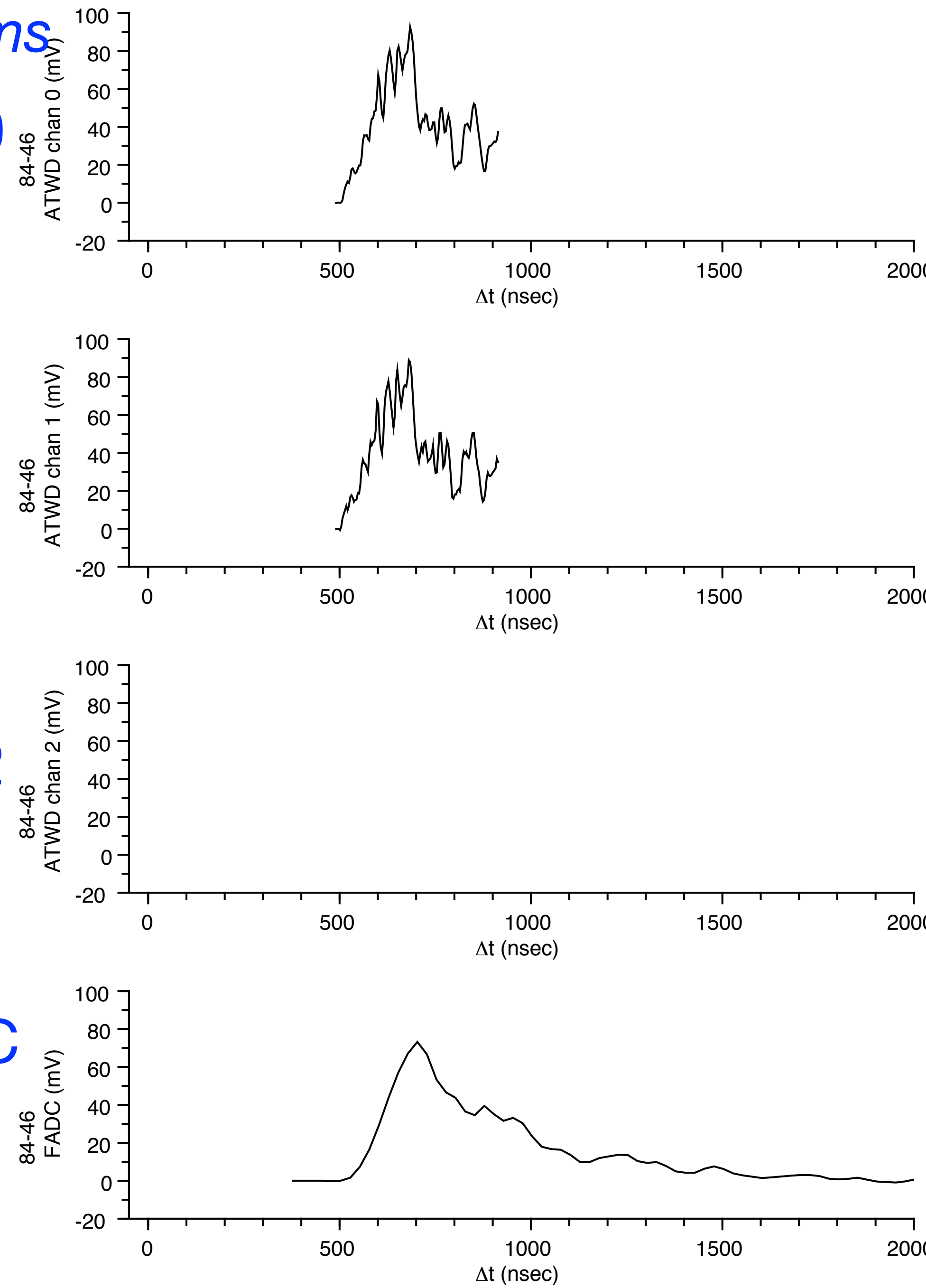




Waveform digitizers “ATWD” Ch. 0,1,2 and “FADC”

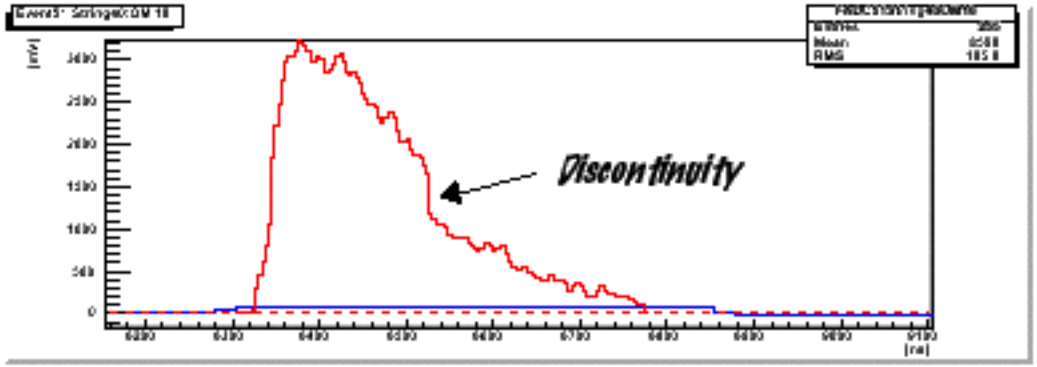
FADC needed for long waveforms





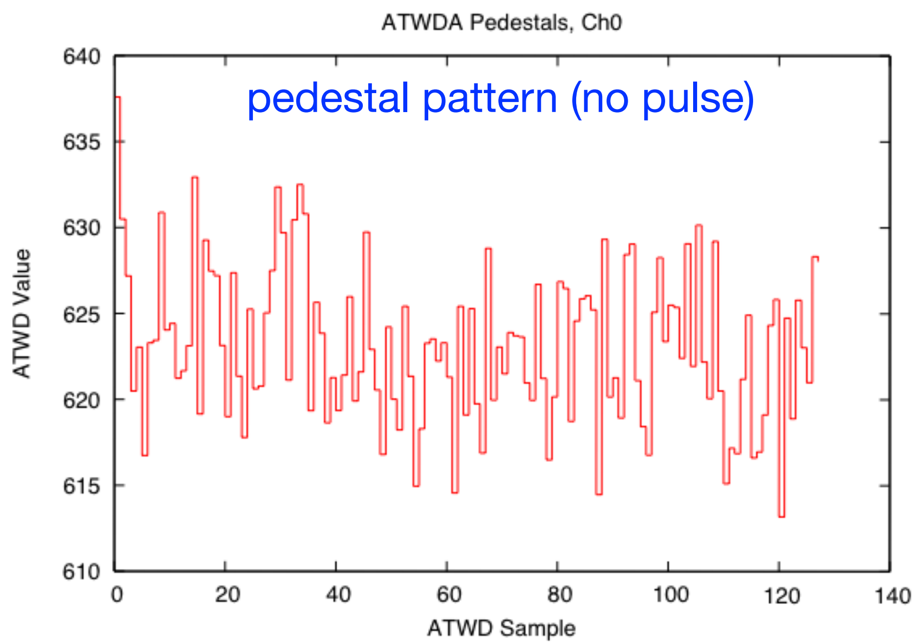
Why so many channels and digitizers?

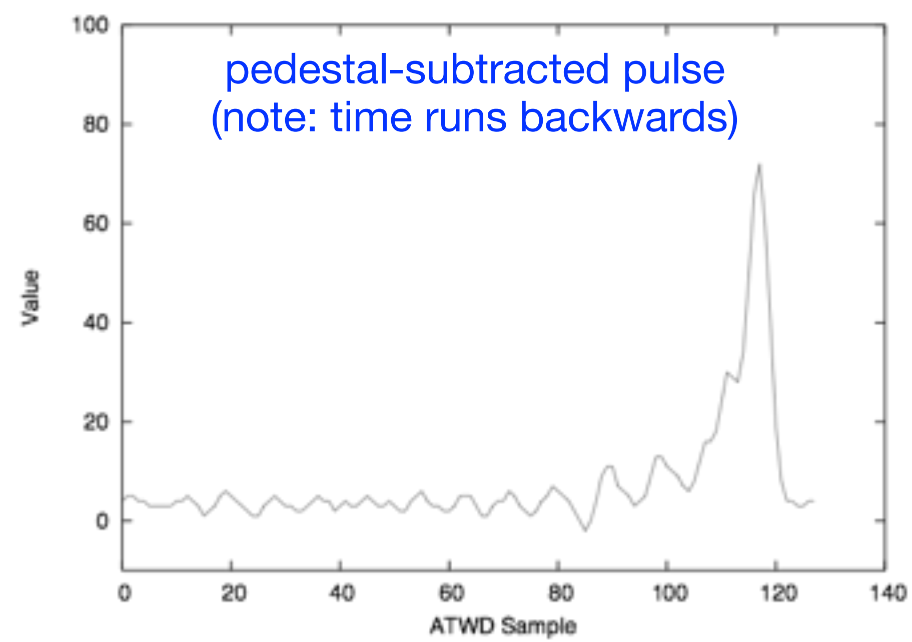
- Fast digitizers are power hungry, and the ATWD design was the alternative
  - When triggered, the ATWD quickly stores 128 samples of waveform, then digitizes these
  - During the digitization period, the ATWD is disabled, so a second one is provided to avoid losing additional hits (“ping-pong”)
- The 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)



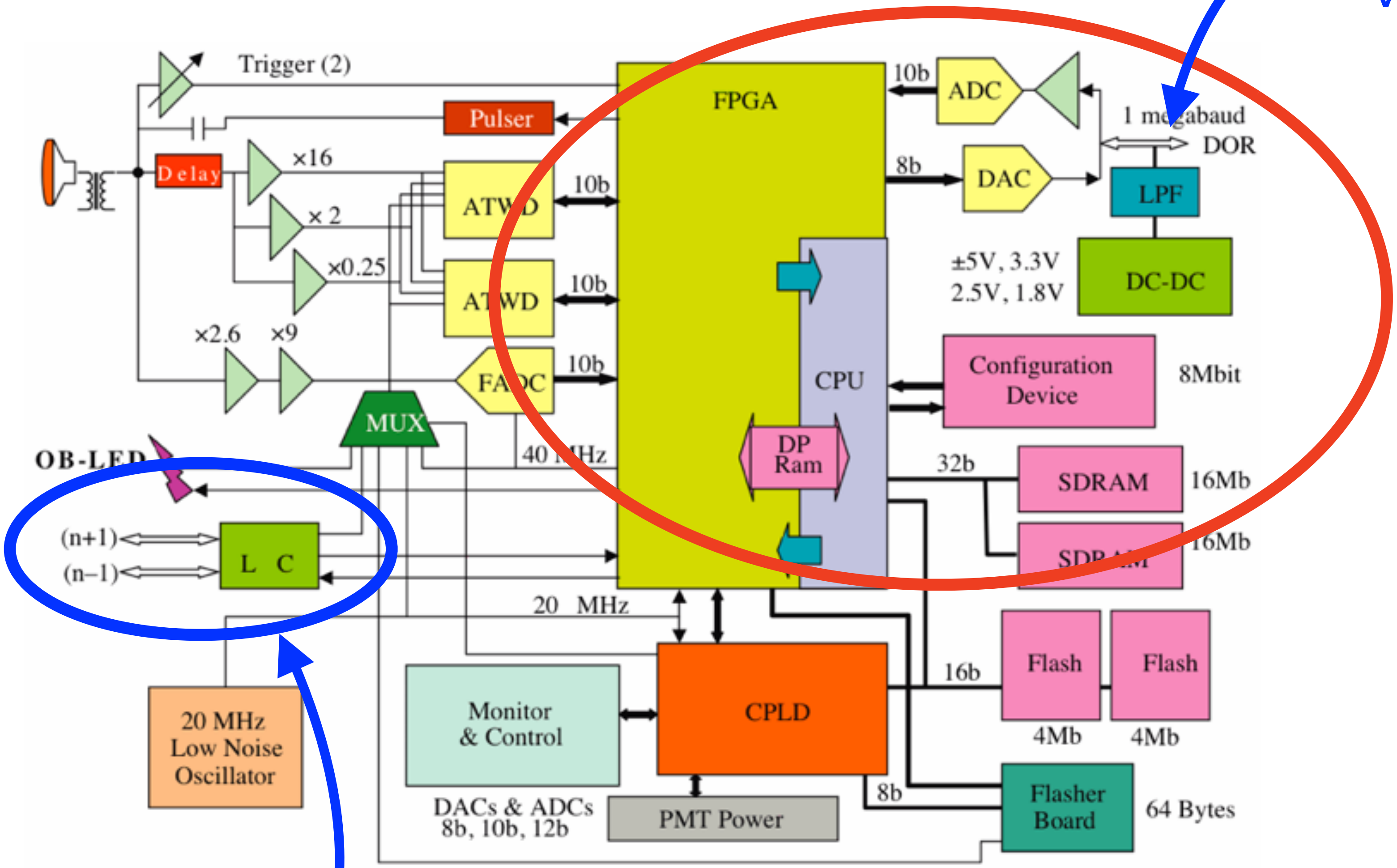


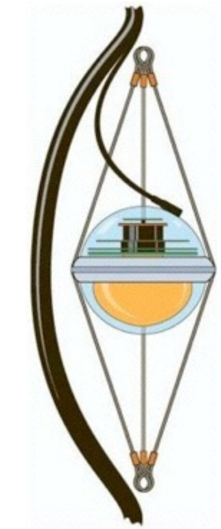
- Baseline voltage is very sensitive to DOM conditions; baselines are measured from previous runs and subtracted before pulses analyzed

- 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

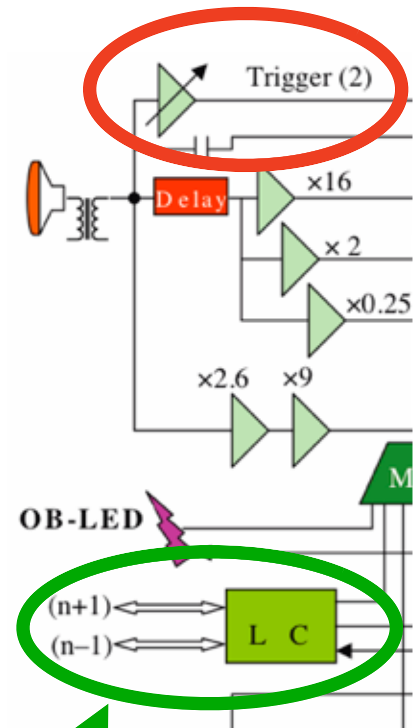
Connection to surface via main cable

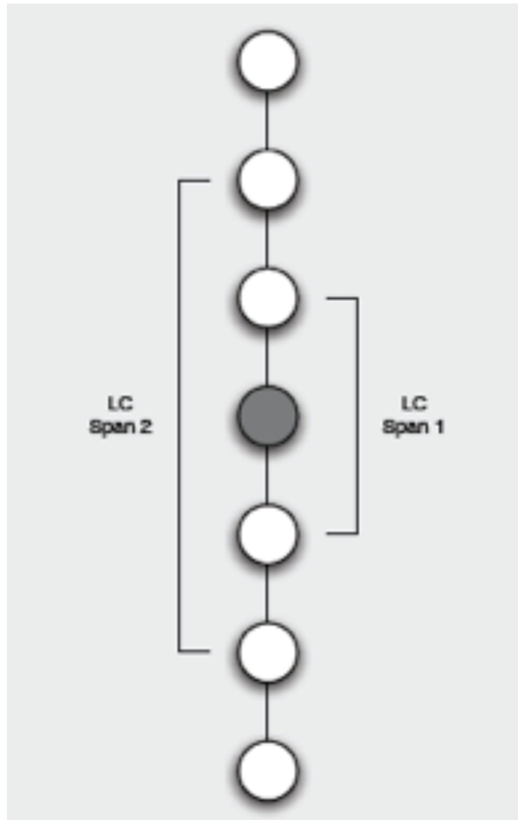


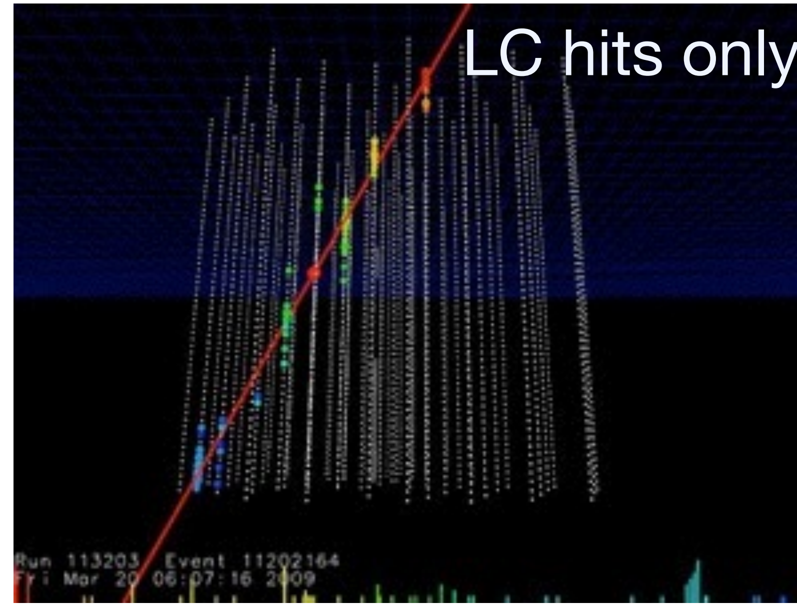


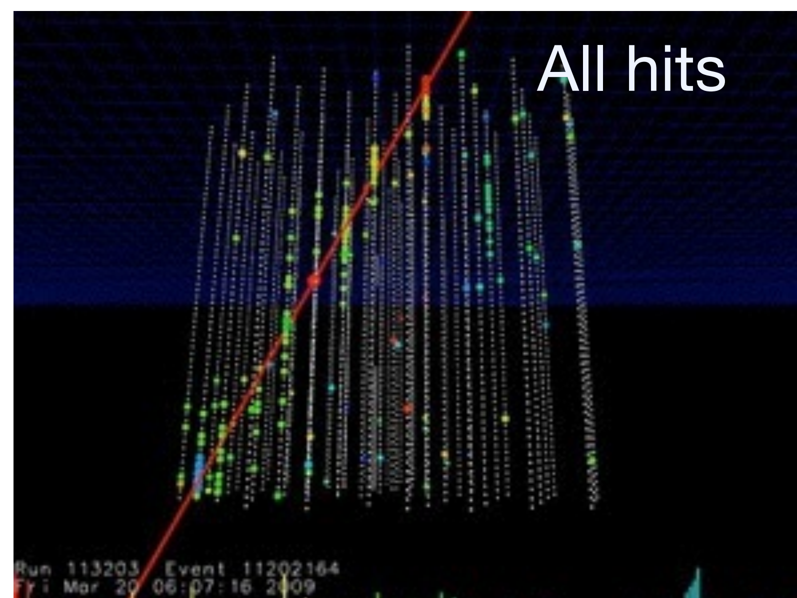
Connection to neighbor DOMs via main cable

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"

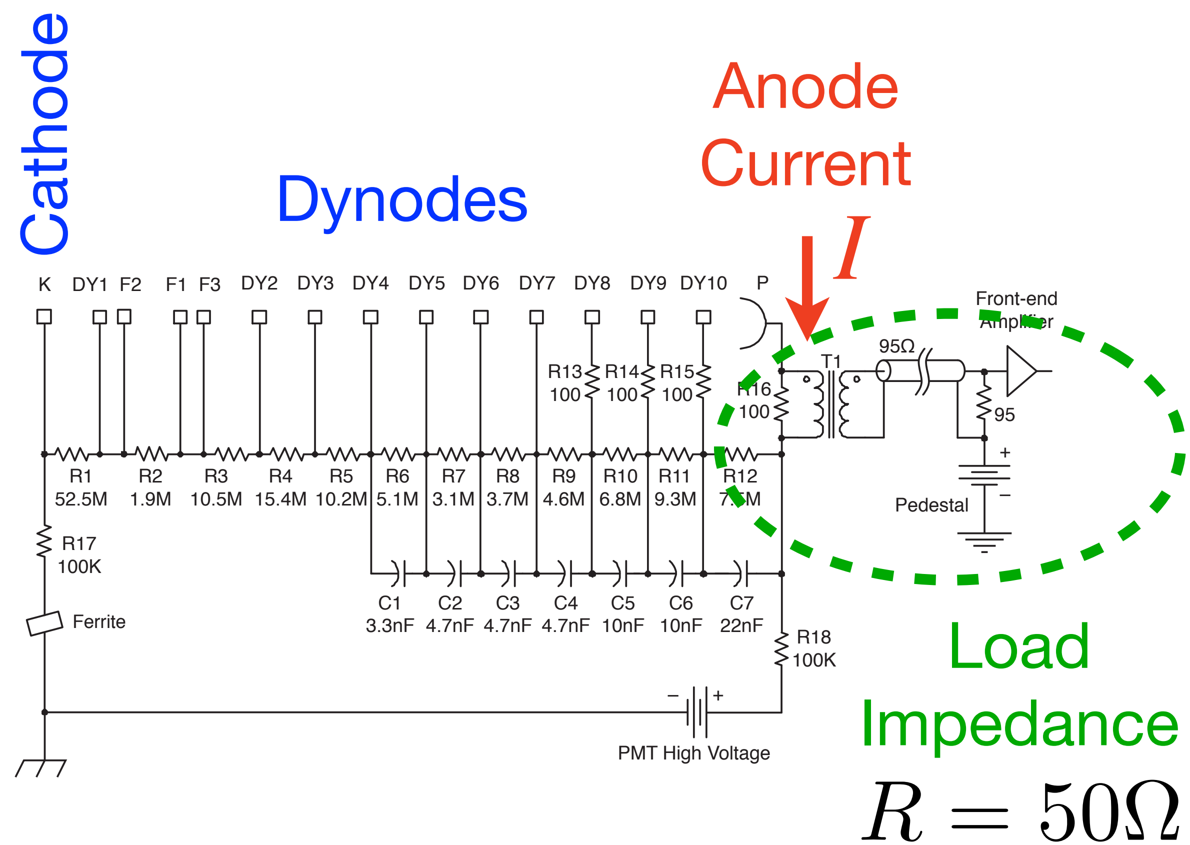
Only three samples of FADC are saved so time of SPE can be determined

- 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

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



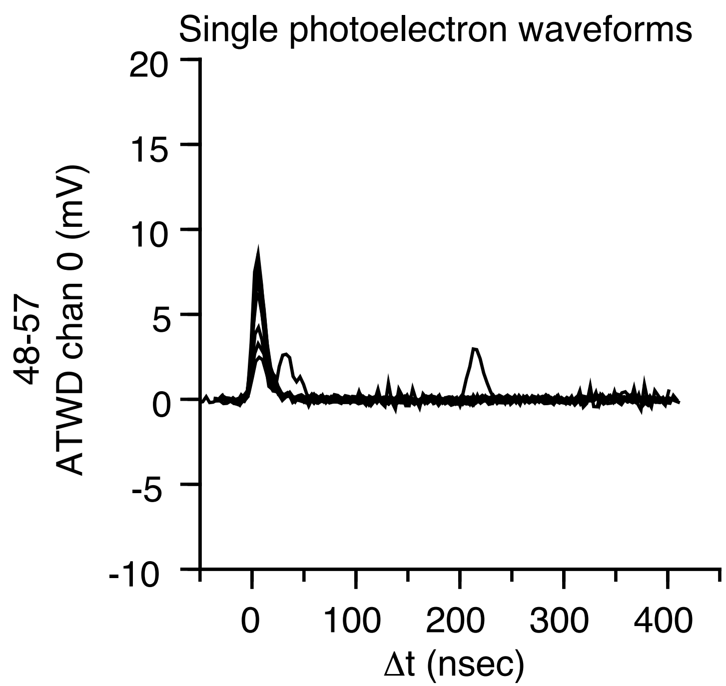
- Units can be pC, or "SPE" where "SPE" = Gain x e

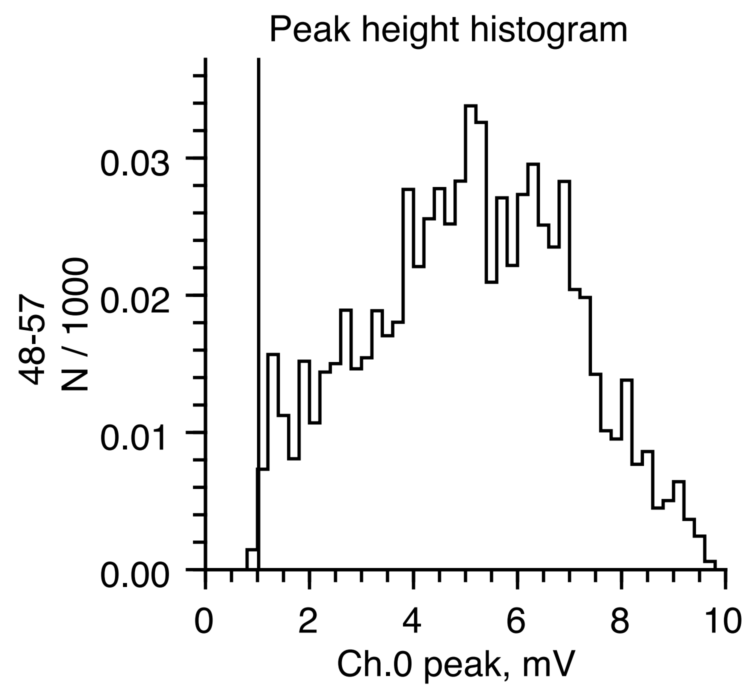
  $= 10^7 \, e$

  $= 1.6$ pC

Reminder of PMT response for single photons

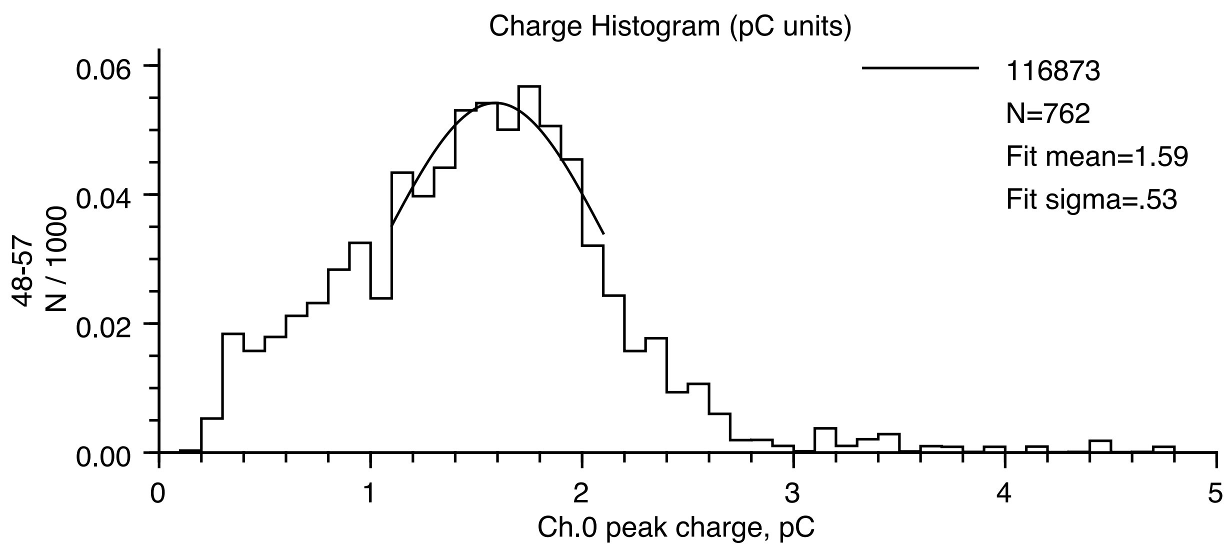
- Pulse heights vary ±30%, with tail on low side

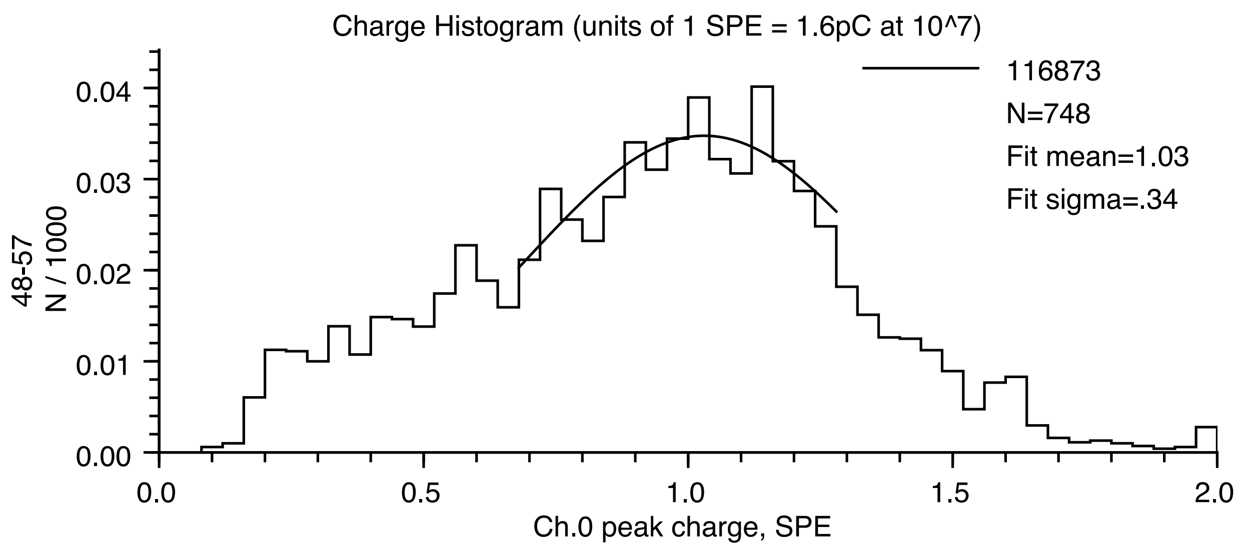




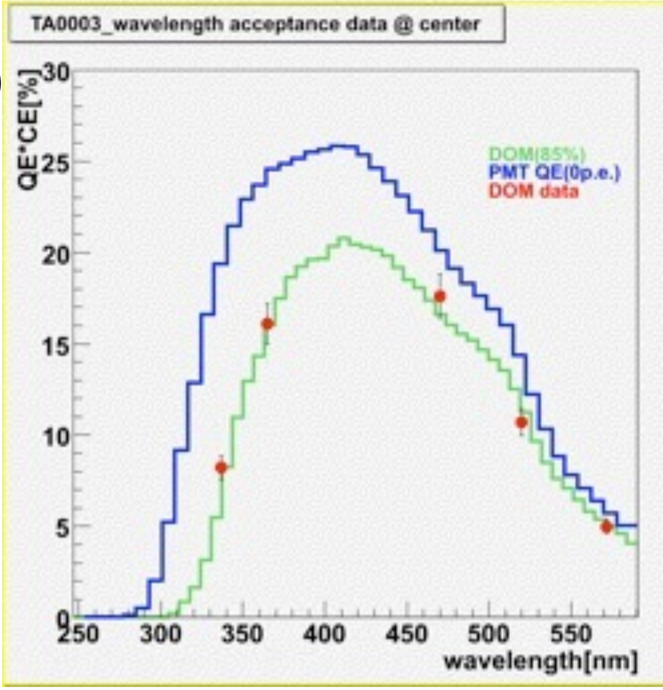
Single photoelectron charge

- 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!



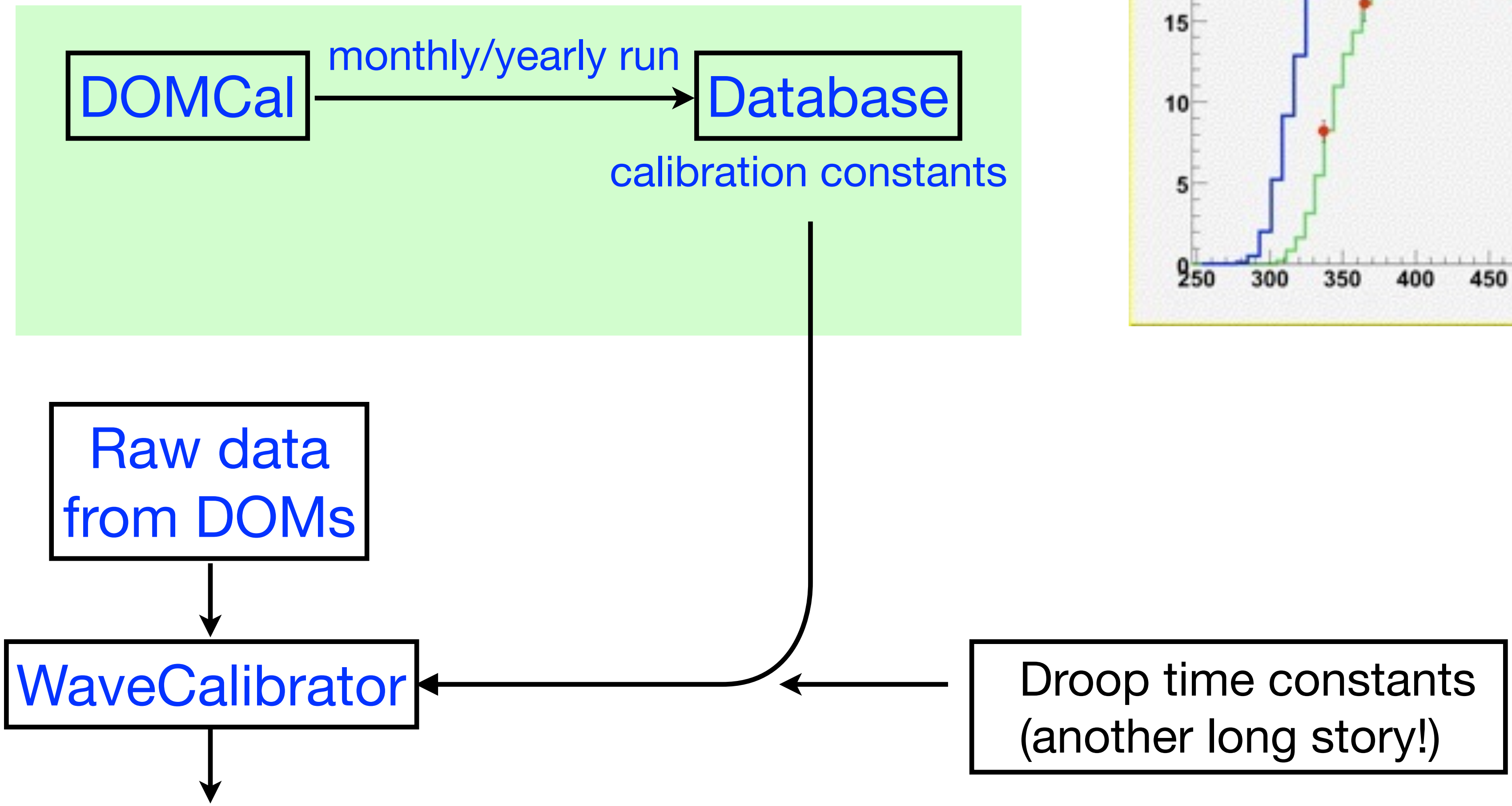


Calibration inputs for counting photons



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

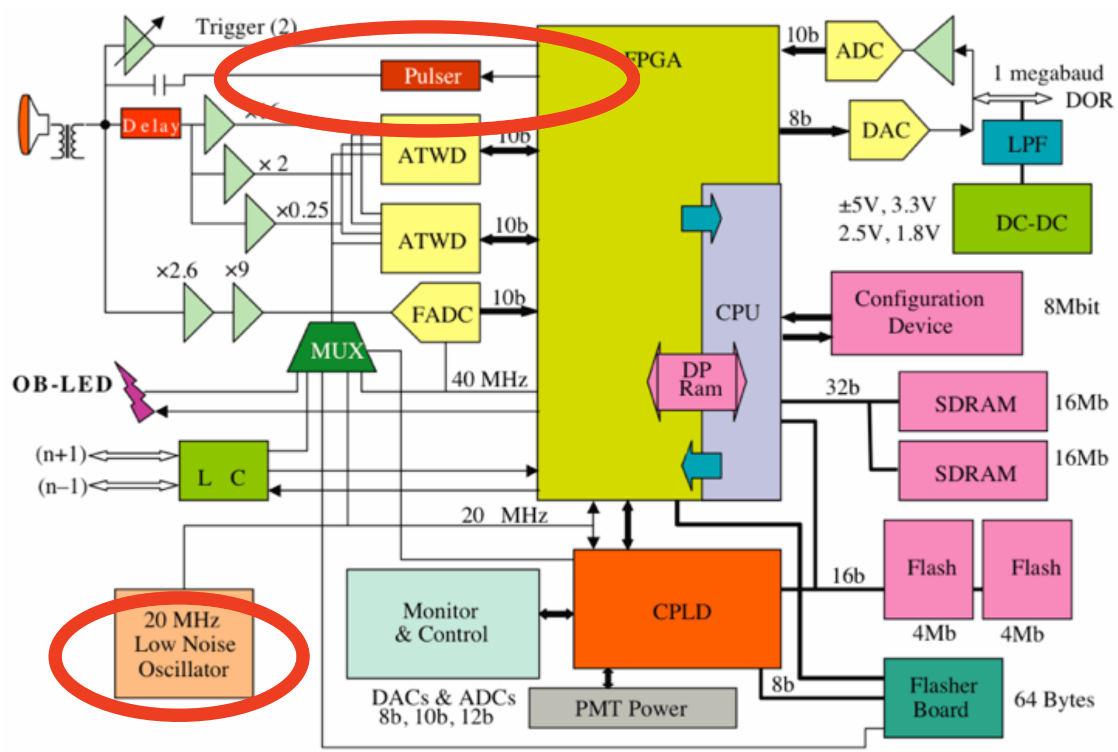
- Calibration of electronic response for SPEs



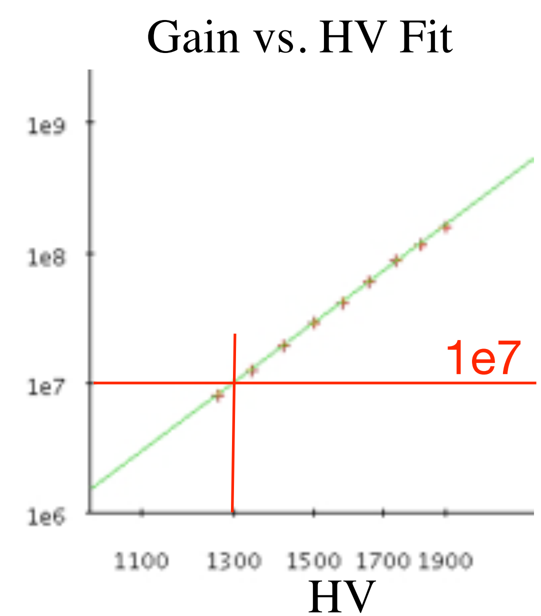
- Waveform analysis software

DOMCal

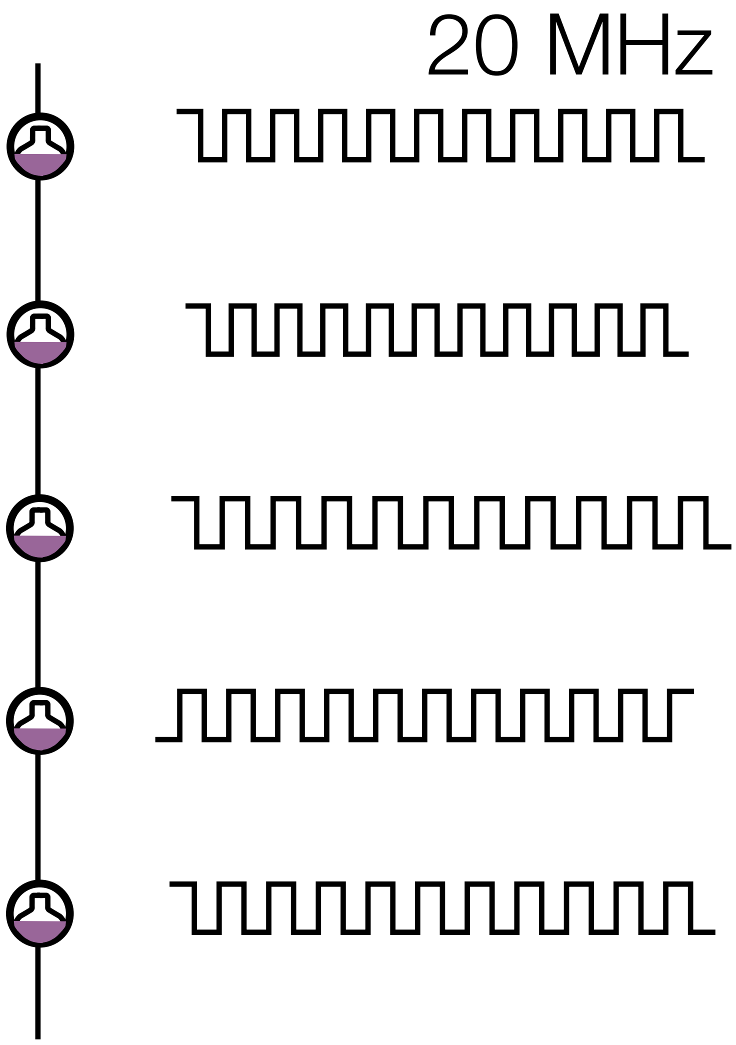
- Written & maintained by Jim Braun, John Kelley, Chris Weaver
- Runs on the DOM mainboard CPU
- Measures calibration constants for converting raw waveform data to millivolts vs. time in nsec



- 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

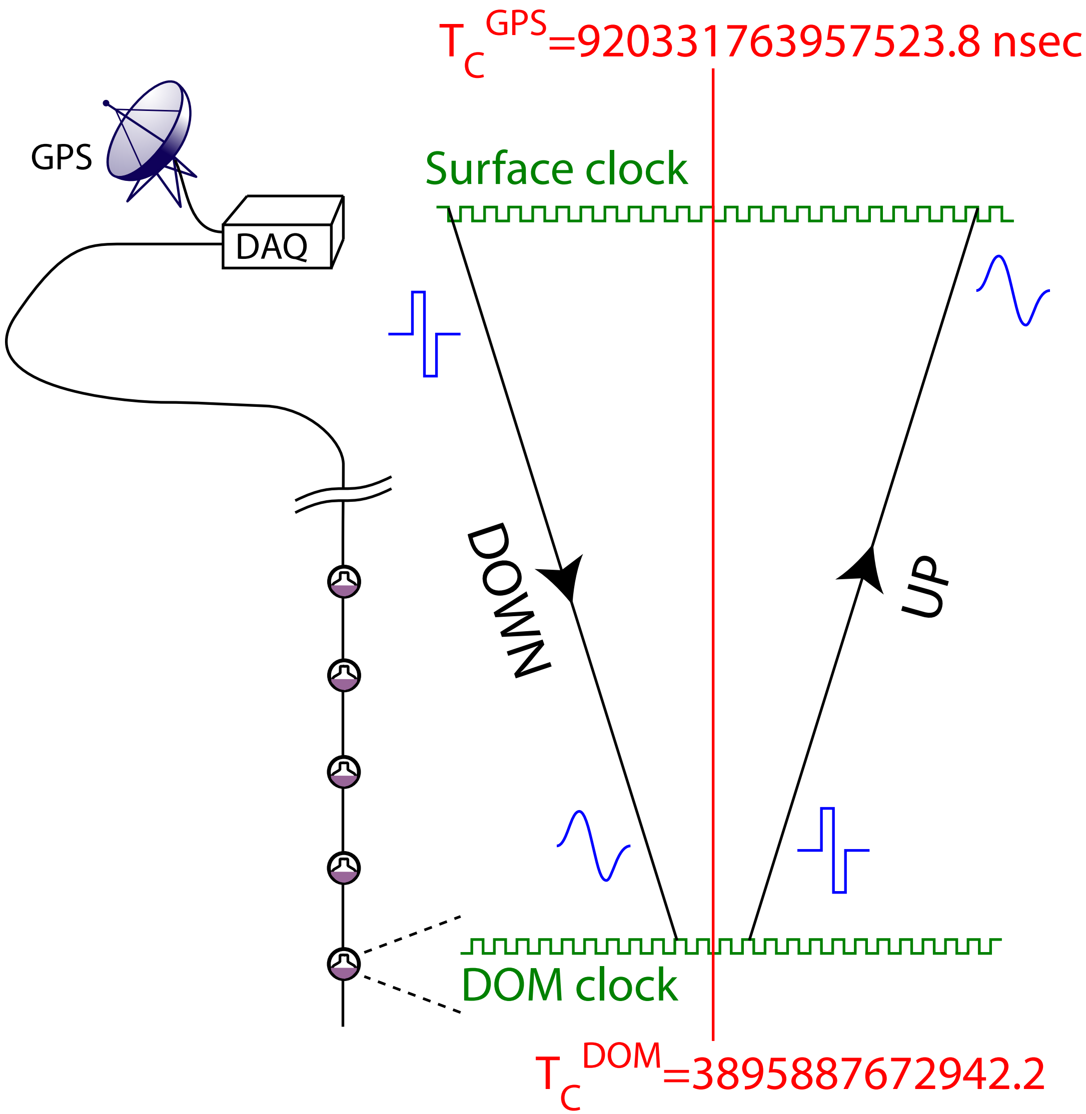
- Very low drift

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

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 1-2 secs

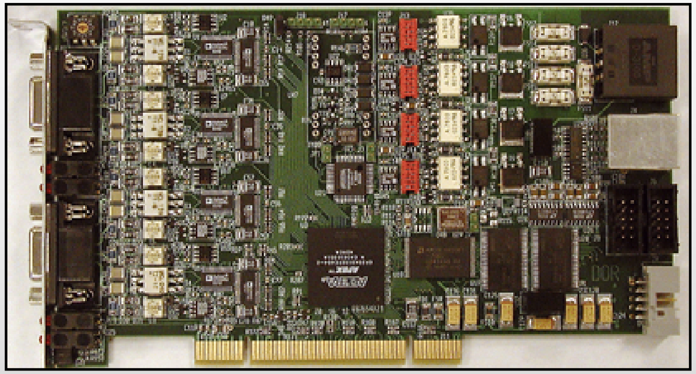
Surface DAQ can correct hit times before recording

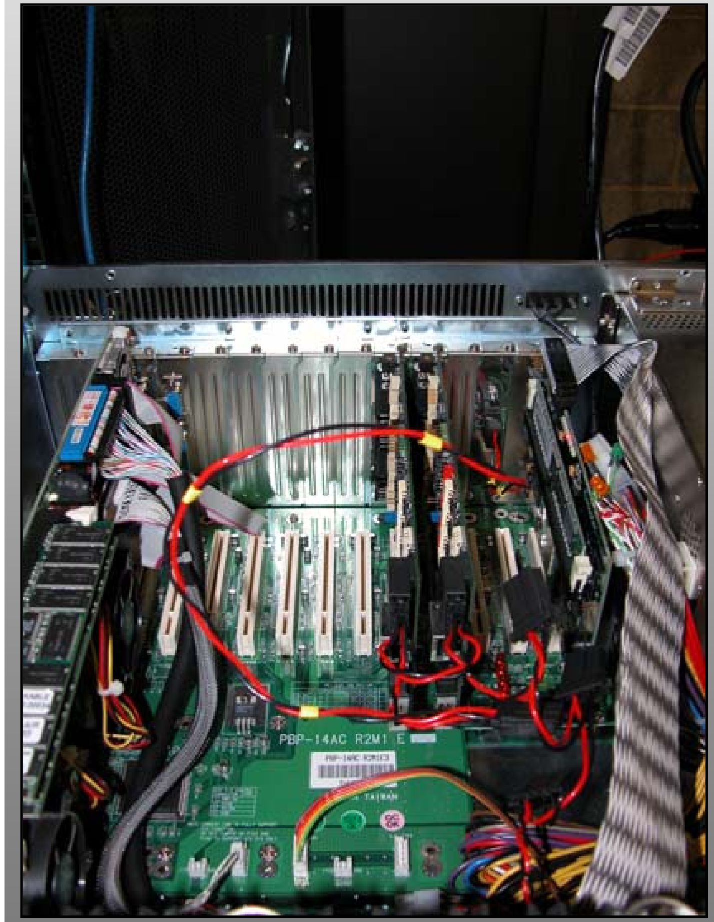
$$T^{GPS} = k\,T^{DOM} + T^{offset}$$

rms of ~2 ns

Talking to DOMs

- DOMs are connected to a PC called a “DOMHub”
- Single-board computer (SBC) with up to 8 custom PCI cards (DOR)
- Up to 8 DOMs connected per DOR
    - 4 wire pairs; 2 DOMs per pair (A/B)
- DOR cards handle power and communications to the DOM
- Interface is via a custom Linux device driver (dor-driver)
- After the hubs... IceCube is a bunch of standard computers!





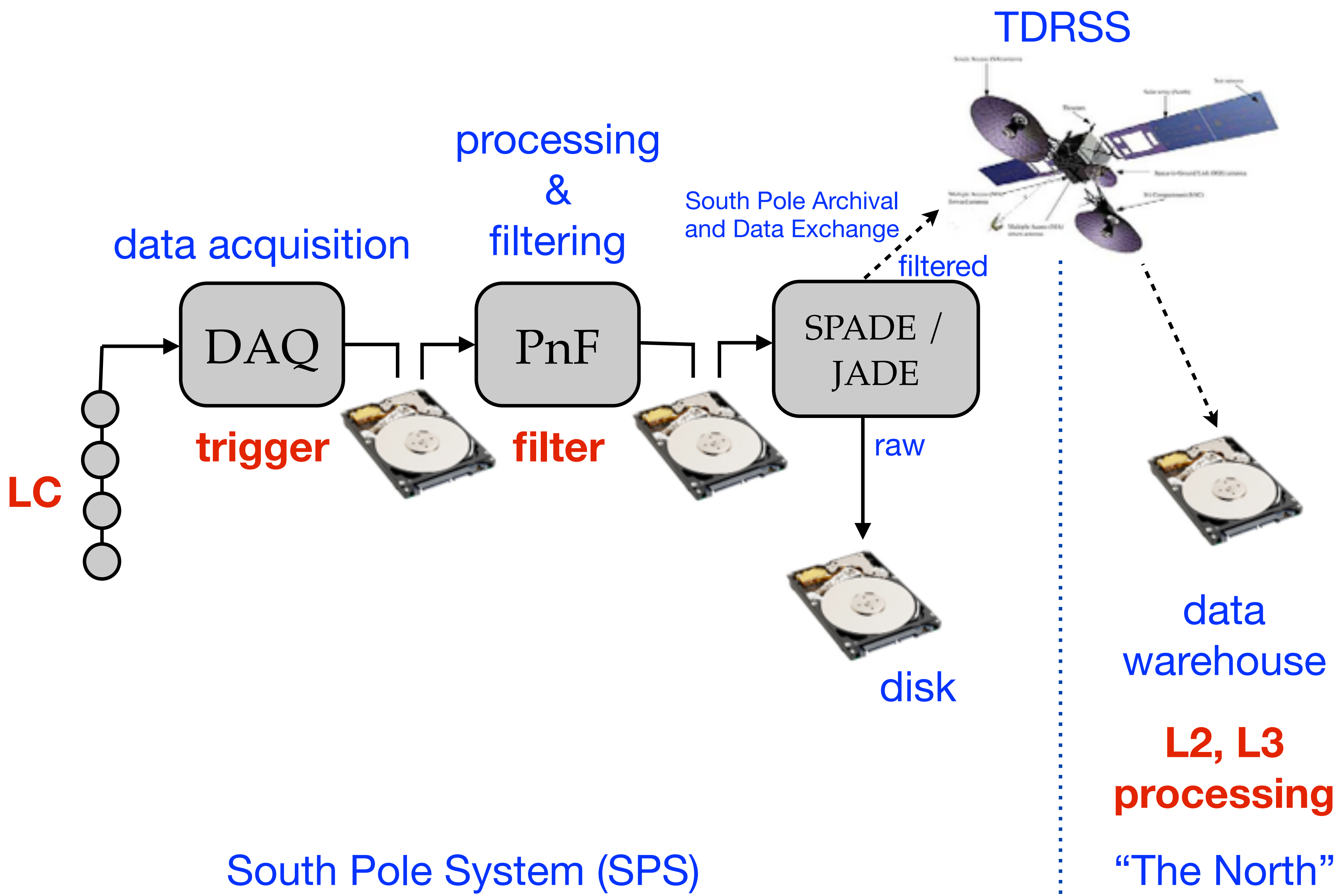
DOMs and the DAQ Demystified
Part II: DAQ, Triggers, Filters, and more

John Kelley
UW-Madison

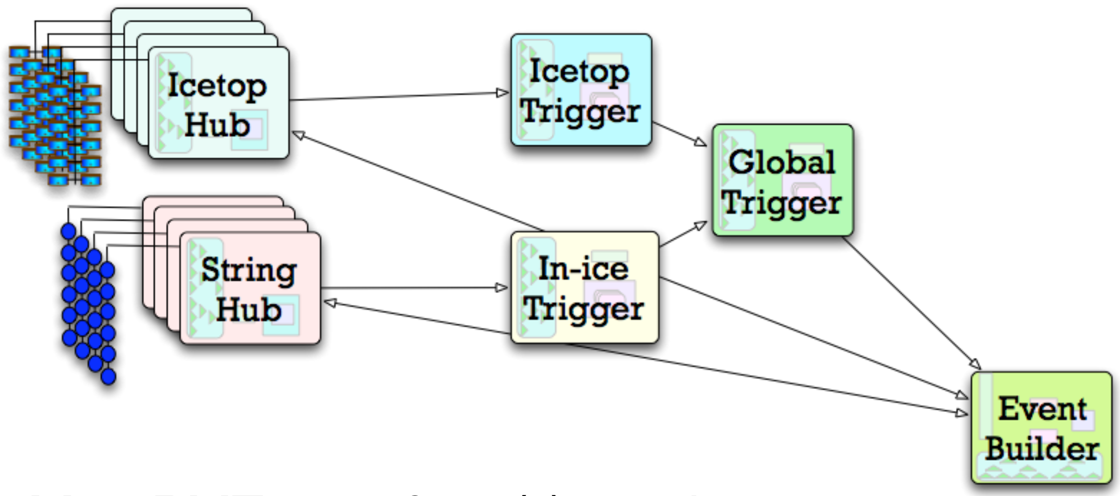
IceCube Bootcamp, 2015-06-09

with thanks to Dave Glowacki, Naoko K. Neilson, Erik Blaufuss

Data flow and reduction



DAQ (Data Acquisition System)



- DOMs generate **hits**: PMT waveform(s) + a timestamp
- We don't want to (and can't) save every hit from every DOM all the time
- The DAQ forms **triggers** when a pattern of hits looks interesting
  - many definitions of "interesting": muons, cascades, air showers, monopoles...
- Individual triggers are combined into a global readout window, or "event"

More info: "Event Triggering in the IceCube Data Acquisition System", VLVnT13, AIP Conf. Proc. **1630**, 154 (2014)
http://dx.doi.org/10.1063/1.4902795

Trigger Types

- **S**imple **M**ultiplicity **T**rigger (SMT)
  - *N* HLC hits or more in a time window
  - Example: InIce SMT8 with N_hits ≥ 8 in 5 μs
  - readout window around this captures early and late hits (-4 μs, +6 μs)

- **String** trigger (a.k.a. Cluster trigger in DAQ-land)
  - *N* HLC hits out of *M* DOMs on a string in a time window
  - Example: 5 hits from a run of 7 adjacent DOMs in a time window of 1500 ns

- **Volume** trigger (a.k.a Cylinder trigger in DAQ-land)
  - simple majority of HLC hits (SMT4) with volume element including one layer of strings around a center string
  - cylinder height is 5 DOM-layers (2 up and down from the selected DOM).

- **Slo**w **P**article trigger (SLOP)
  - slow-moving hits along a track
  - lengths of the order of 500μs and extending up to milliseconds

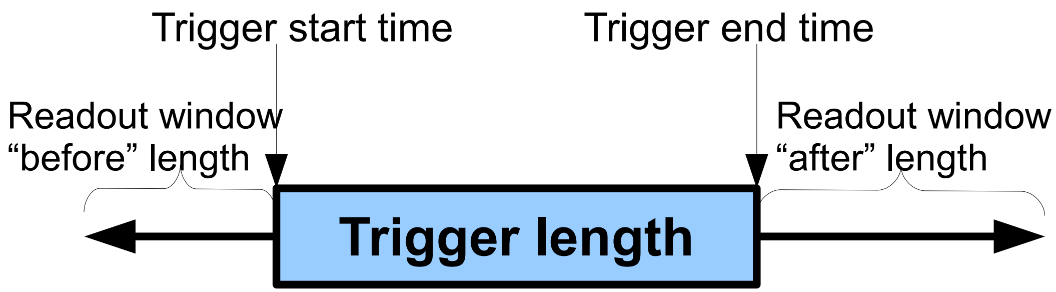
- **F**ixed **R**ate **t**rigger, **Min**imum **Bias** trigger, **Calibration** trigger

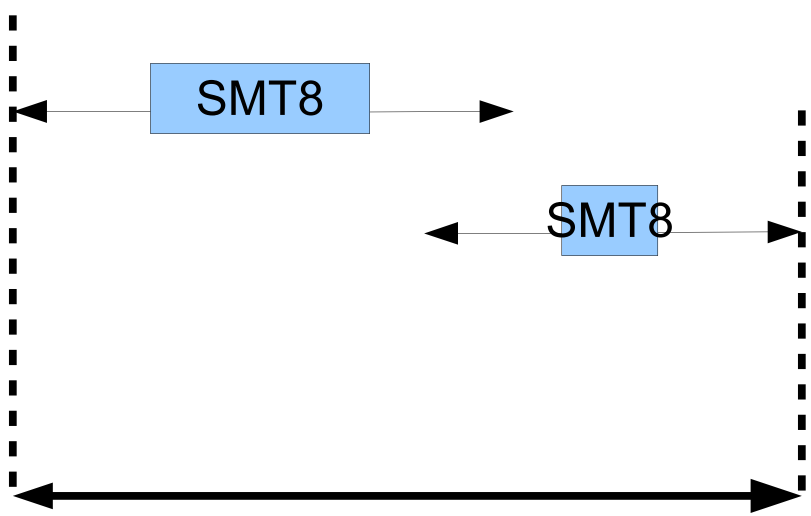
Trigger rate example

Trigger	Rate (Hz)
InIce SMT8	2113
DeepCore SMT3	256
SLOP	13.3
FRT	0.0333
String	2240
Volume	3727
MinBias	59.4

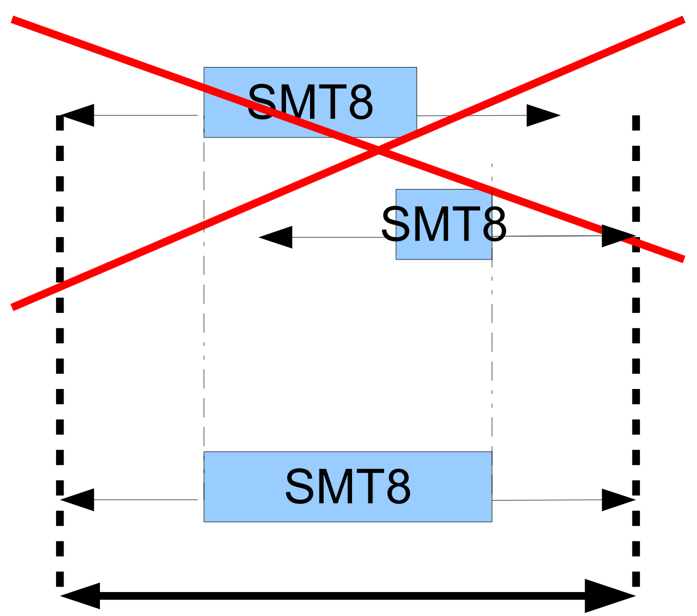
DAQ InIce trigger rates from Run 120029

Trigger Readout





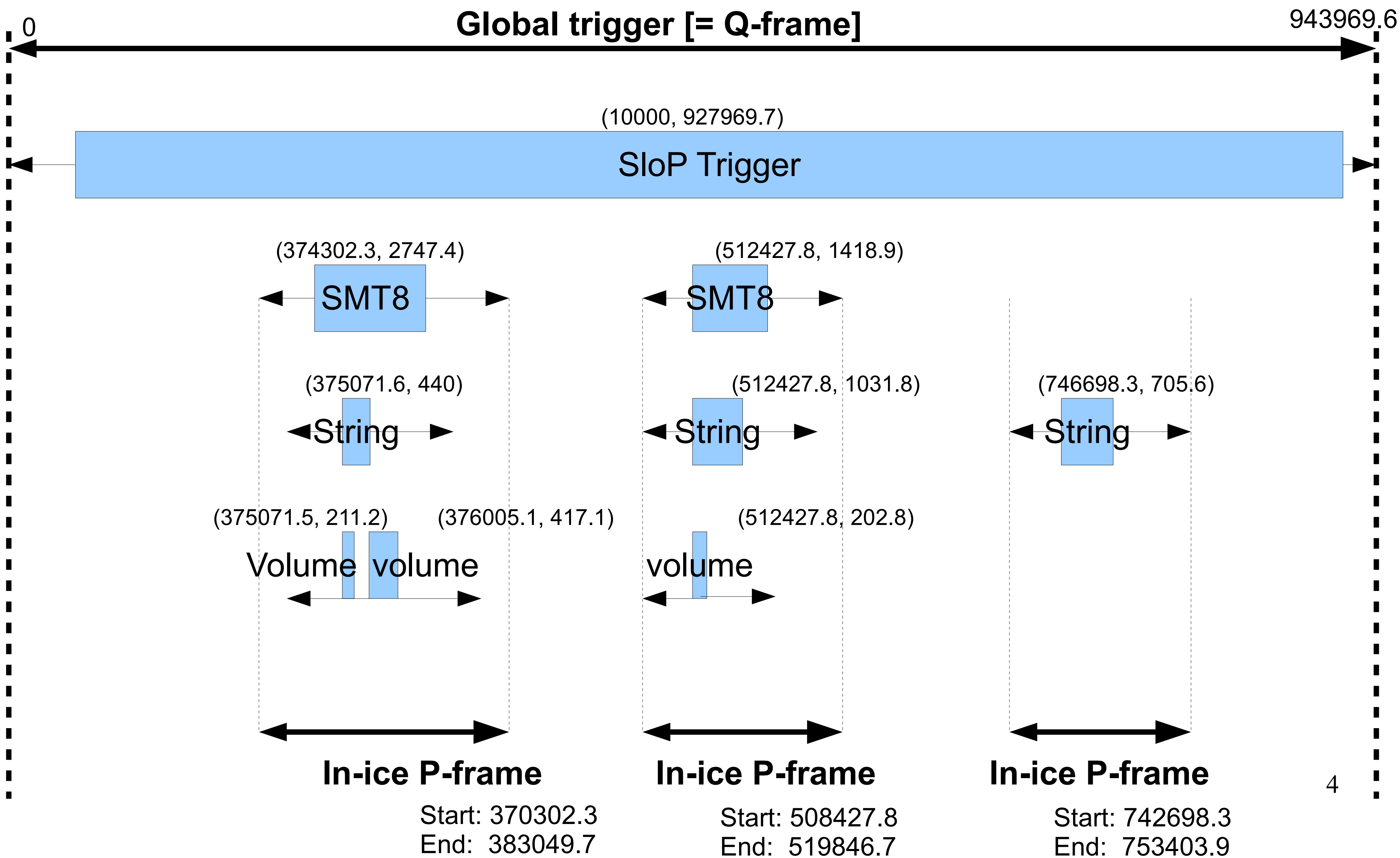
Global Trigger Readout = one Frame



Global Trigger Readout = one Frame

Example global trigger

Real data from 2011 (trigger time, trigger length) in ns



Trigger rate example

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InIce SMT8	2113
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SLOP	13.3
FRT	0.0333
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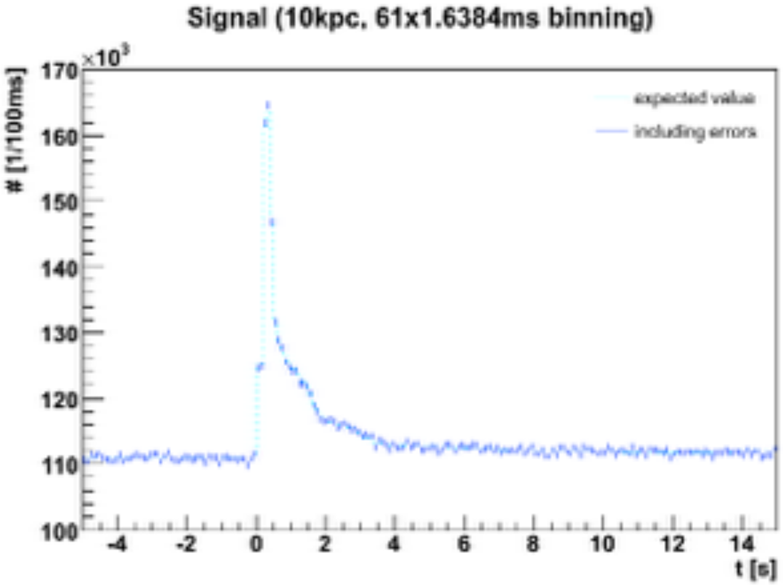
Volume	3727
MinBias	59.4

Event rate from Run 120029: 2742 Hz

SNDAQ



- IceCube can also detect nearby supernovae: detection method very different
- The **S**uper**n**ova **DAQ** runs in parallel to the "normal" DAQ after the StringHubs
- Collects noise rates vs. time for all in-ice DOMs
  - looks for global rise in noise rates across detector
  - sends alerts over Iridium satellite constellation to SNEWS
  - sends SMS alerts and e-mails

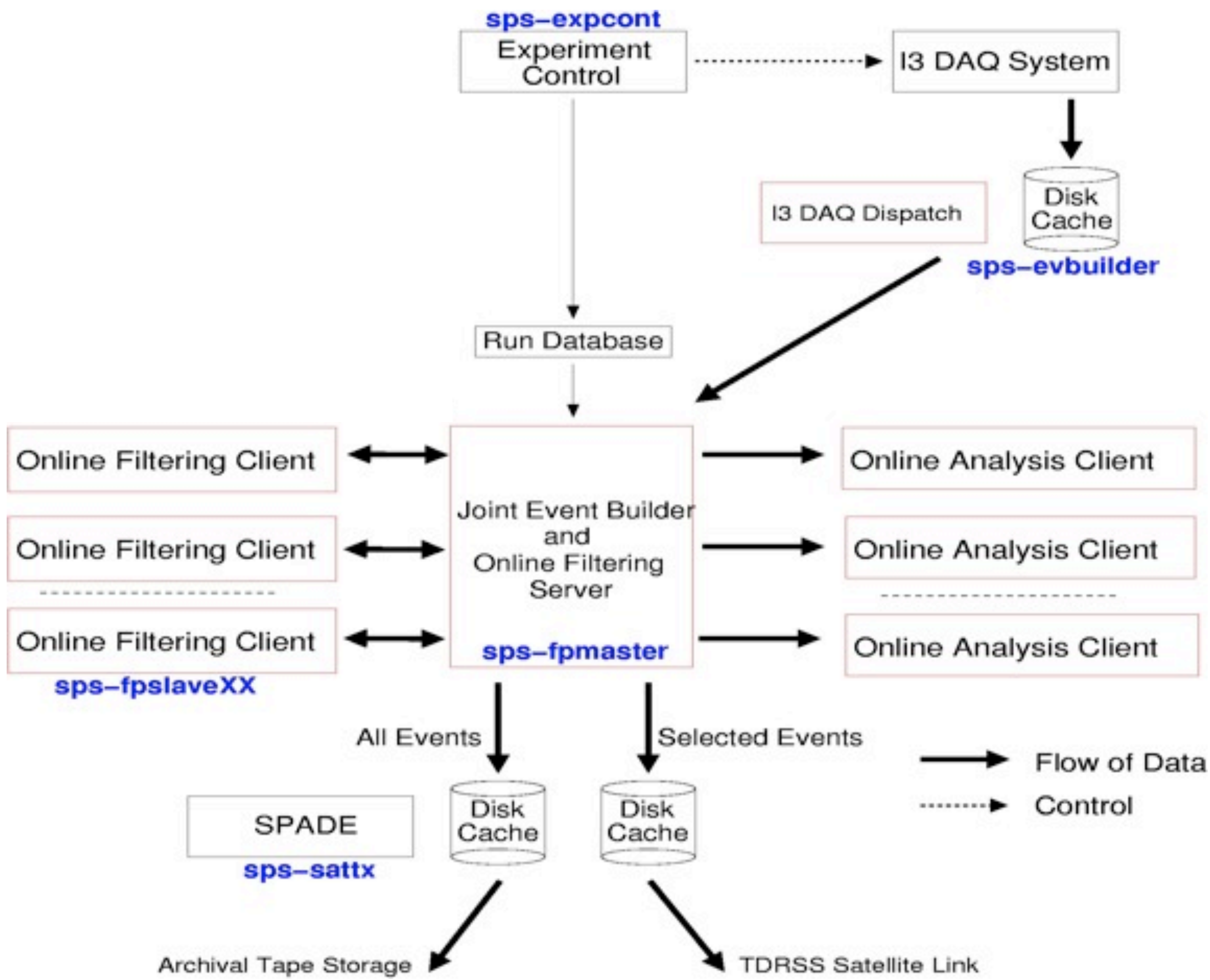
Online Filtering

- DAQ "raw" output: almost 1 TB/day
  - recall: vast majority of these are cosmic-ray muons
- TDRSS (satellite) bandwidth allocation for IceCube: 105 GB/day
- Options:
  - wait until we can fly the tapes out (what if there's a problem with the data?)
  - run **filtering** online to look for interesting events; send subset of data over satellite
- **Bonus!** Can trigger other experiments for near-real-time followup
  - optical followup alerts to ROTSE
  - gamma-ray followup alerts to MAGIC

What is a filter?

- A **filter** is the first stage of analysis that looks for a type of physics event at SPS, to send over the satellite
- Each working group proposes its own filter: muon, cascade, etc.
- The filters are run by **PnF**, which calibrates and cleans the data, looks for events containing triggers that the filters are interested in
  - fast, first-guess algorithms run on most events
  - loose “quality cuts” throw away the junk
- PnF then farms the events out to a computer cluster at pole

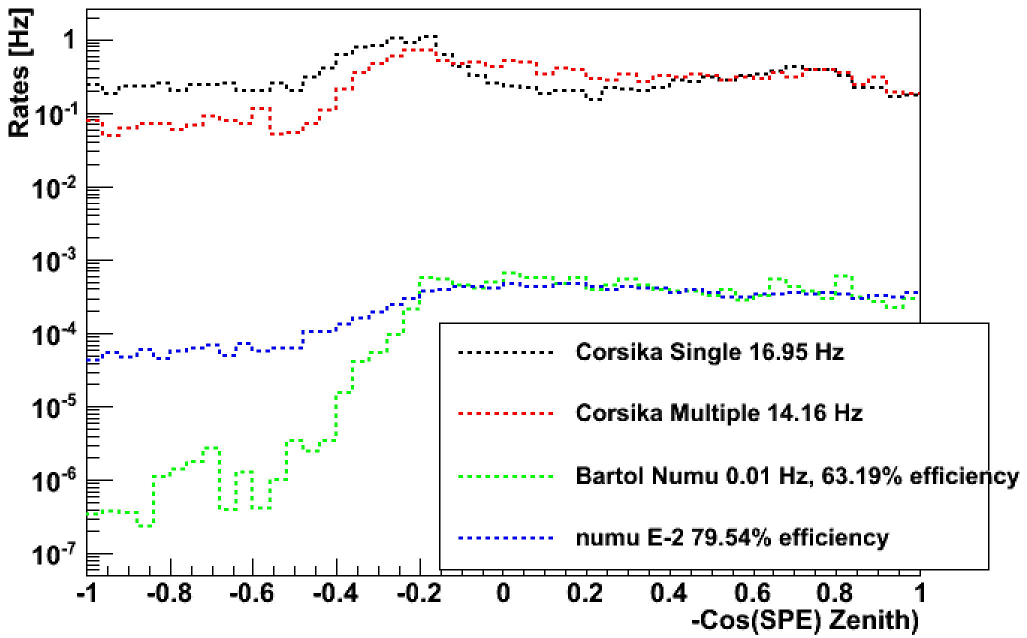
Processing and Filtering (PnF)



Filter Examples (not exhaustive!)

- Muon filter
  - hit cleaning -> calibration -> pulse extraction -> fast track reconstruction -> direction-dependent quality cuts
- Cascade filter
  - events that look more blob-like than track-like (tensor of inertia ratio)
- EHE filter
  - high-energy events (total NPE)
- Sun & Moon filter
  - events coming from current Sun and Moon position (WIMPs, moon shadow)
- IceTop filter
  - quality air shower events (also: in-ice coincidences)
- quite a few others for specific analyses

Muon Filter Passing Rate (simulation)

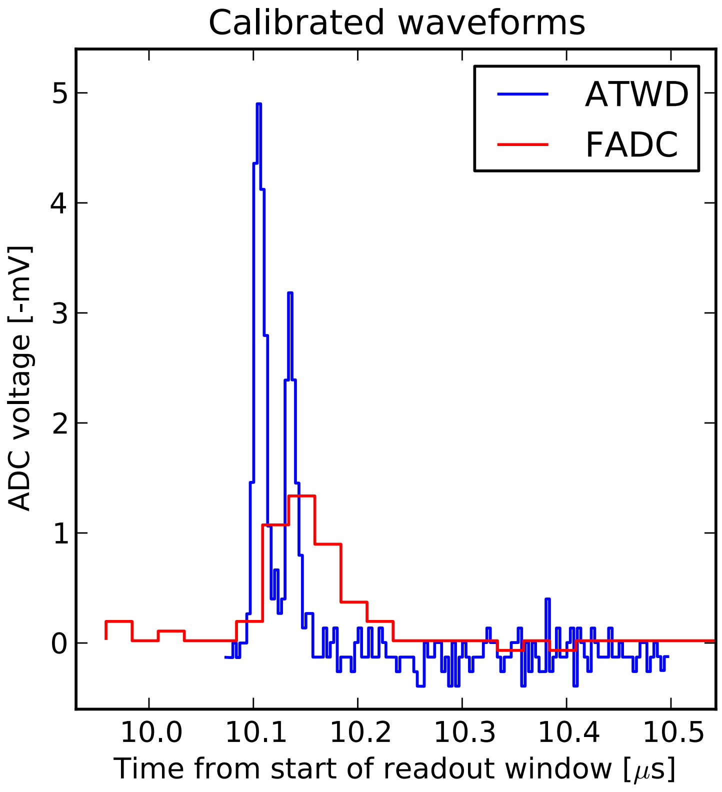


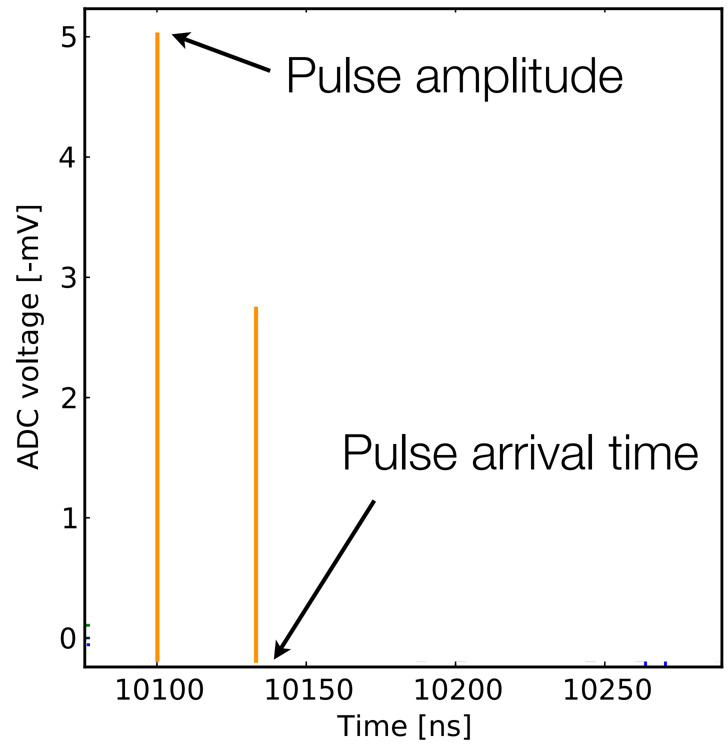
SuperDST

- Basic idea: send highly compressed version of almost every triggered event
  - send reconstructed pulses, not raw waveforms

- Extension of **D**ata **S**torage and **T**ransfer format previously used in IceCube

- Deployed large-scale in 2012; can replace a number of other filters





all you need for many events!

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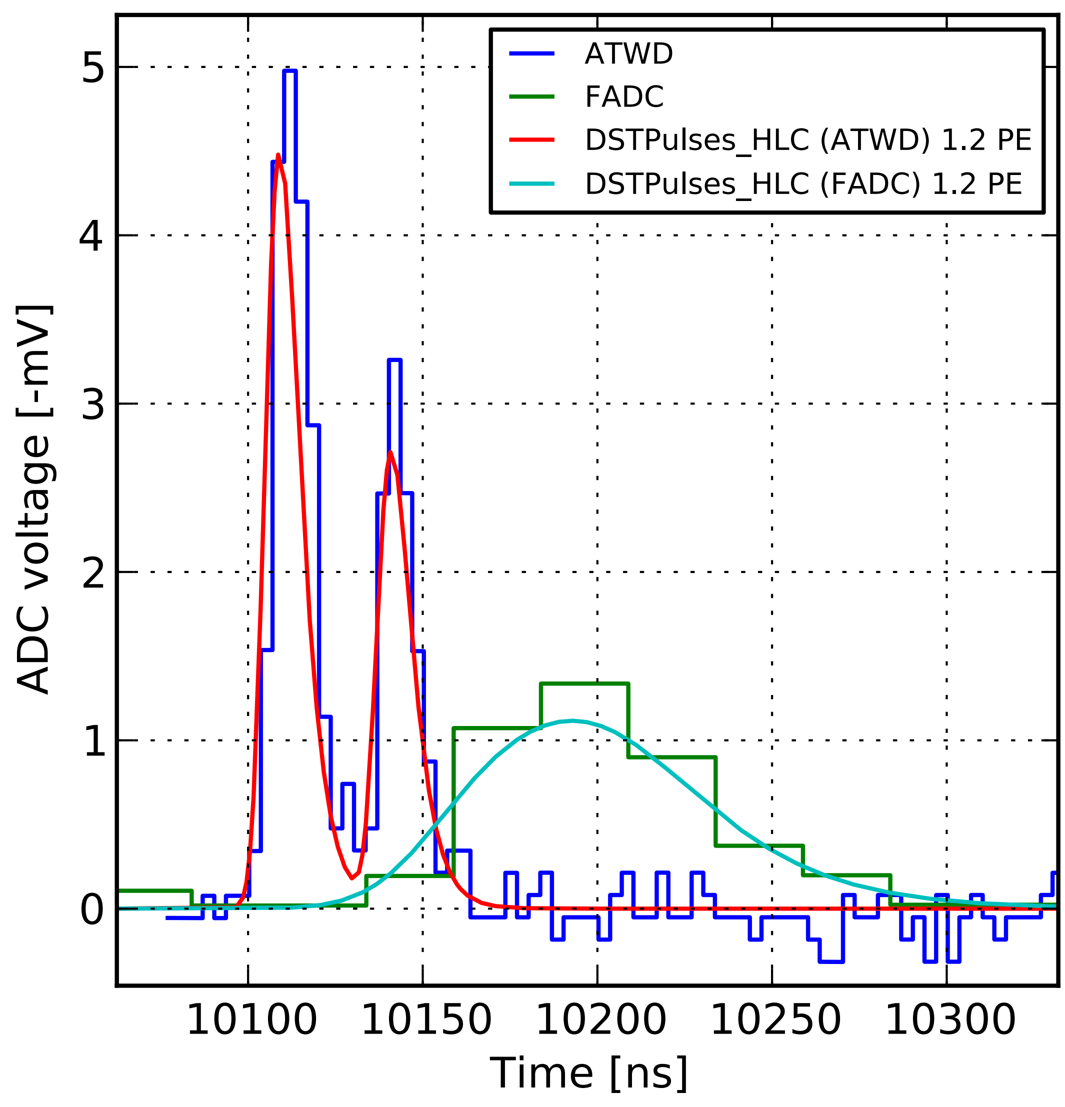
SuperDST reconstructed waveforms

Raw payload: **4394 bytes**

SuperDST: **414 bytes**



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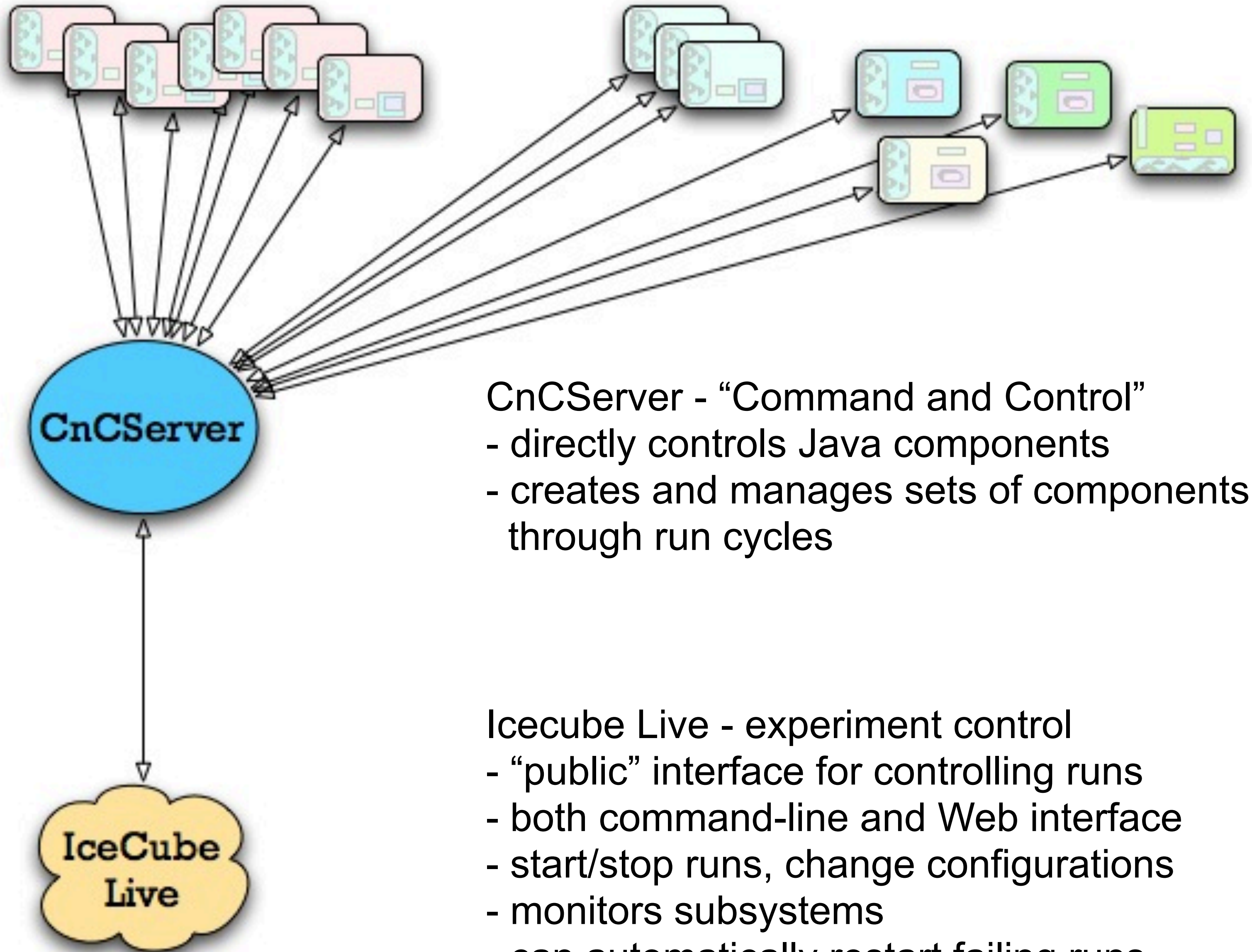
Triggering, **F**iltering, and **T**ransmission Board

- How to balance needs of everyone wanting:
  - special DAQ trigger
  - special physics event filter
  - lots of satellite bandwidth

- TFT board reviews proposals once a year

- Wiki is a good place to start for trigger / filter descriptions
  http://wiki.icecube.wisc.edu/index.php/Trigger_Filter_Transmission_Board

Experiment Control and I3Live



CnCServer - “Command and Control”
- directly controls Java components
- creates and manages sets of components through run cycles

Icecube Live - experiment control
- “public” interface for controlling runs
- both command-line and Web interface
- start/stop runs, change configurations
- monitors subsystems
- can automatically restart failing runs

Another look at Live:

http://live.icecube.wisc.edu

Some sources for more information

- Previous years' boot camp presentations
  http://wiki.icecube.wisc.edu/index.php/Bootcamp

- IceCube PMT Paper
  https://docushare.icecube.wisc.edu/dsweb/Get/Document-53922/

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

- Wiki page for LED flashers
  http://wiki.icecube.wisc.edu/index.php/Flashers

- Docushare areas and personal websites
  Docushare: https://docushare.icecube.wisc.edu/dsweb/View/Collection-410
  Jerry Przybylski: http://icecube.lbl.gov/~gtp/site_map.html#ForIceCube
  Thorsten Stezelberger: http://glacier.lbl.gov/~thorsten/ATWD/
  Nobuyoshi Kitamura: http://icecube.wisc.edu/~kitamura/

- N.B. many more details being taken care of like "toroid droop", baseline offsets, channel non-matching, PMT saturation, afterpulses, more precise optical sensitivity measurement, ...

Some sources for more information

- I3Live documentation:
  https://live.icecube.wisc.edu/doc/main/

- TFT proposals:
  http://wiki.icecube.wisc.edu/index.php/Trigger_Filter_Transmission_Board

- SuperDST:

  http://wiki.icecube.wisc.edu/index.php/SuperDST
  https://events.icecube.wisc.edu/indico/contributionDisplay.py?contribId=140&sessionId=4&confId=33

- Supernova DAQ:
  http://wiki.icecube.wisc.edu/index.php/Supernova

- Monitoring:

  http://wiki.icecube.wisc.edu/index.php/Monitoring

- Problem DOMs:

  http://wiki.icecube.wisc.edu/index.php/Problem_DOMs