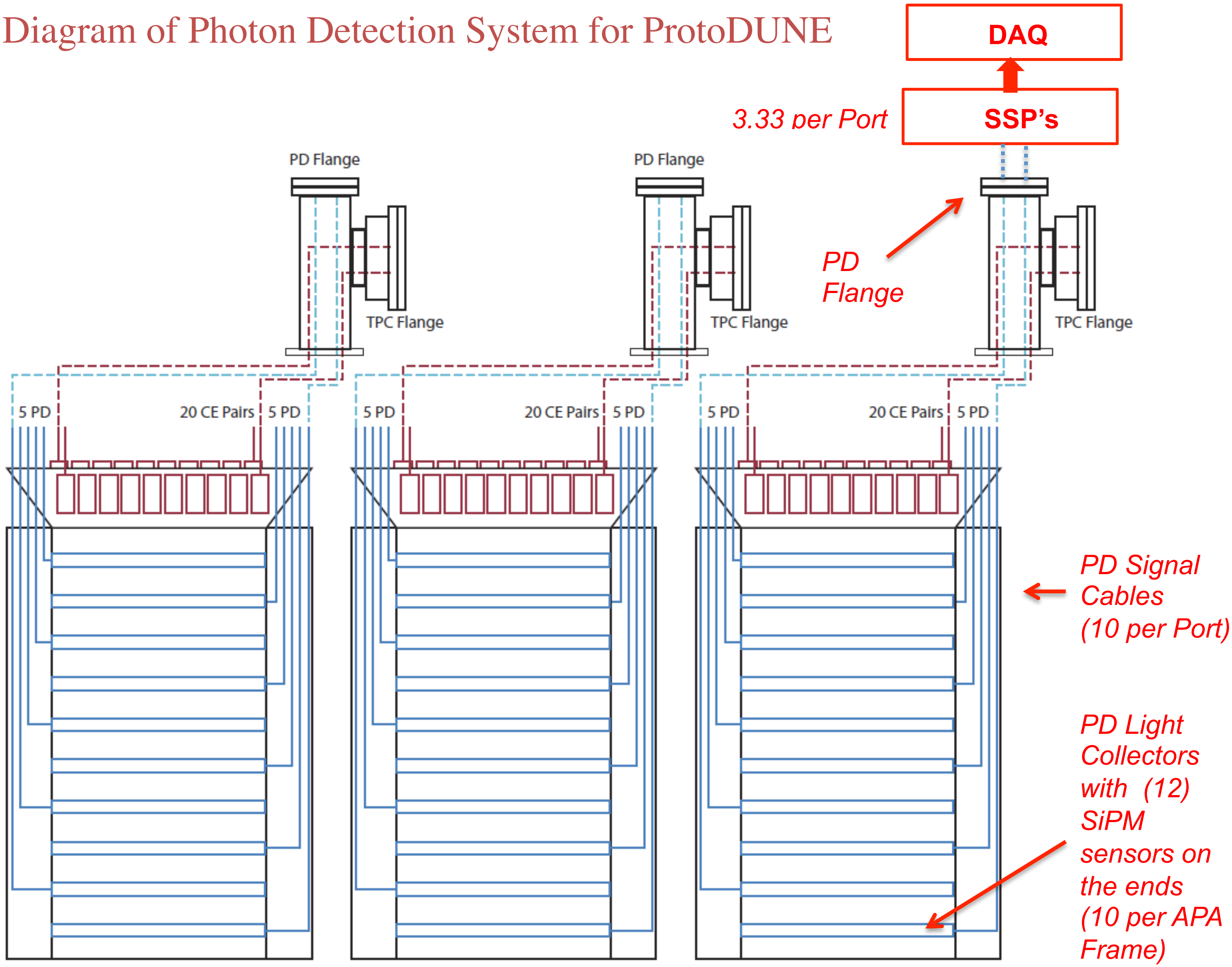
SP Photon Detector System Readout: ProtoDUNE System and DAQ Interfaces

Zelimir Djurcic, Gary Drake, Mike Oberling, Ranjan Dharmapalan

Talk Overview

- Photon Detector Readout Concept and Requirements
- Overview of the Readout Architecture
- DAQ Interfaces
- ProtoDUNE Photon-Detector Signal Cables and Connectors
- ProtoDUNE Photon-Detector Signal Feed-thru
- Power and Bias
- ProtoDUNE Photon-Detector Grounding Plan
- Summary Design choices to mitigate noise risks
- Photon readout characterization tests at ANL
- Delivery of the components to CERN
- ProtoDUNE DAQ and Cold Box tests
- Thoughts on going from ProtoDUNE to DUNE readout
- Summary

Block Diagram of Photon Detection System for ProtoDUNE



⇨ *No Cold Electronics in the PD system!*

Physics Requirements

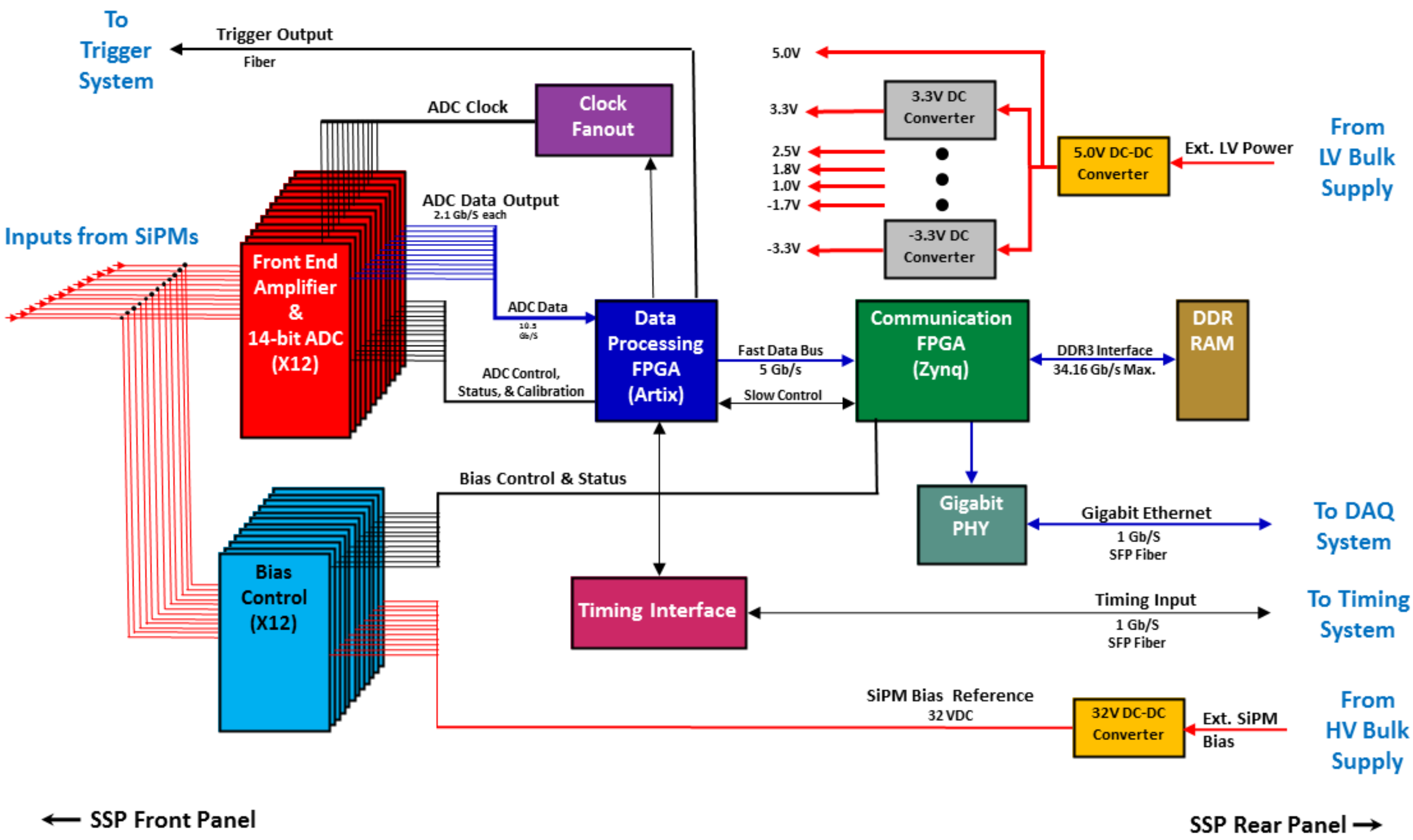
- Initially very wide-ranged, led R&D through ProtoDUNE
  - -Goal was to support a wide range of R&D to help define the ultimate requirements
  - -Lead to realization of ProtoDUNE

Performance Parameter	Initial Target	Achieved (35-ton)
Time Resolution	< 30 nS wrt T0	~2-3 nS on single pe*
Charge Resolution	0.25 pe equiv.	66 nA @ 150 MSPS
Dynamic Range	1000:1 (pe equiv)	14-bit
Linearity	Sufficient to resolve 1 pe	< 1 % INL; < 1 ADC count DNL
Multi-Hit Capability	Sufficient to measure Triplet (late) photons	Continuous waveform sampling, 13 uS buffer @ 150 MSPS
Dead Time	Live up to 2 drift times either side of beam spill	No dead time up to 30 KHz/ch (1000 samples/event)
Bias Control	0.1V resolution up to 30V per channel	0.1V resolution up to 30V per channel
Calibration	On-board charge injection	On-board charge injection
Timing Interface	Time-stamp events	ProtoDUNE Timing System interface

Details on initial requirements given in the LBNE docdb-7605, "Working Draft of Photon Detection System Electronics Requirements", N. Buchanan, Z. Djurcic, G. Drake, M. Johnson, B. Jones, J. Klein, J. Musser, S. Seibert.

Block Diagram of the Readout Architecture

- ProtoDUNE Readout Board (SSP)



Overview of ProtoDUNE SSP

Rear Panel

View with top cover removed

Front Panel

Overview of ProtoDUNE SSP (Cont.)

Status Indicators

Comm &
Timing

Front Panel

Power

Fiber optic
Reset Input

Power Switch

Channel Activity/Status Indicators

Fiber optic
Trigger Output

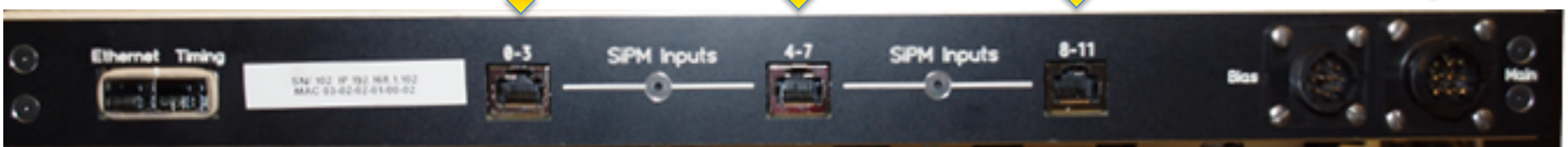
Overview of ProtoDUNE SSP (Cont.)

Rear Panel

GbE (SFP)

SiPM connections (RJ45, signal + bias)

Bulk power input



Timing Interface (SFP)

Bias power input

Why not cold?

- We did not go cold for the 35-ton Detector & ProtoDune because:
  - The original tight schedule precluded this R&D
  - With SiPM gains of 1E7, the S/N ratio was acceptable over long cables
  - Wanted to minimize the digital noise in the cryostat
  - The ganging of 3 SiPMs together into 1 readout channel made the cable plant manageable for ProtoDune
  - In general, having the electronics accessible in the warm environment makes for a more robust system
  - The exclusive use of warm electronics greatly reduced the infrastructure and requirements inside the cryostat, including simpler mechanical design, no heat load concerns, reduced problems with electrical connections and cable routing, etc.
- What about for DUNE?:
  - Should consider cold front-end amplifiers that can actively sum SiPM signals…

DAQ Interfaces

- ProtoDUNE Implementation
  -All DAQ interfaces on fiber to isolate from noise sources.

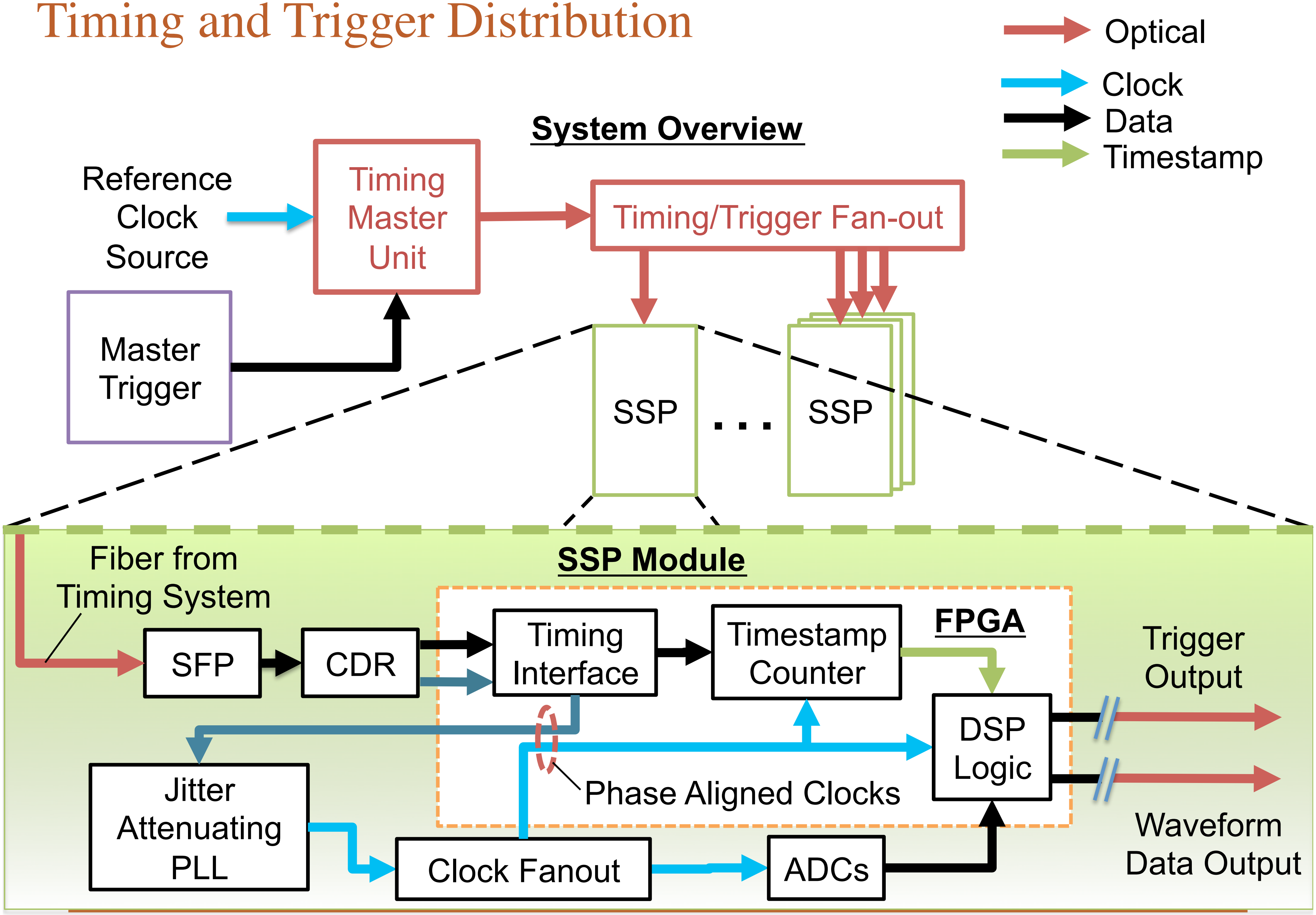
- Timing/Trigger
  -Fiber timing interface to receive timestamp and clock from a central timing system.

- Ship out all the data we get in the beam spill, as fast as possible
  -Existing Gate, Event, Trigger, Spill (GETS) logic is example of what's implemented
  -Gbps lanes for data, shipped out to Board Readers
  -Same Gbps lanes for slow control and monitoring.

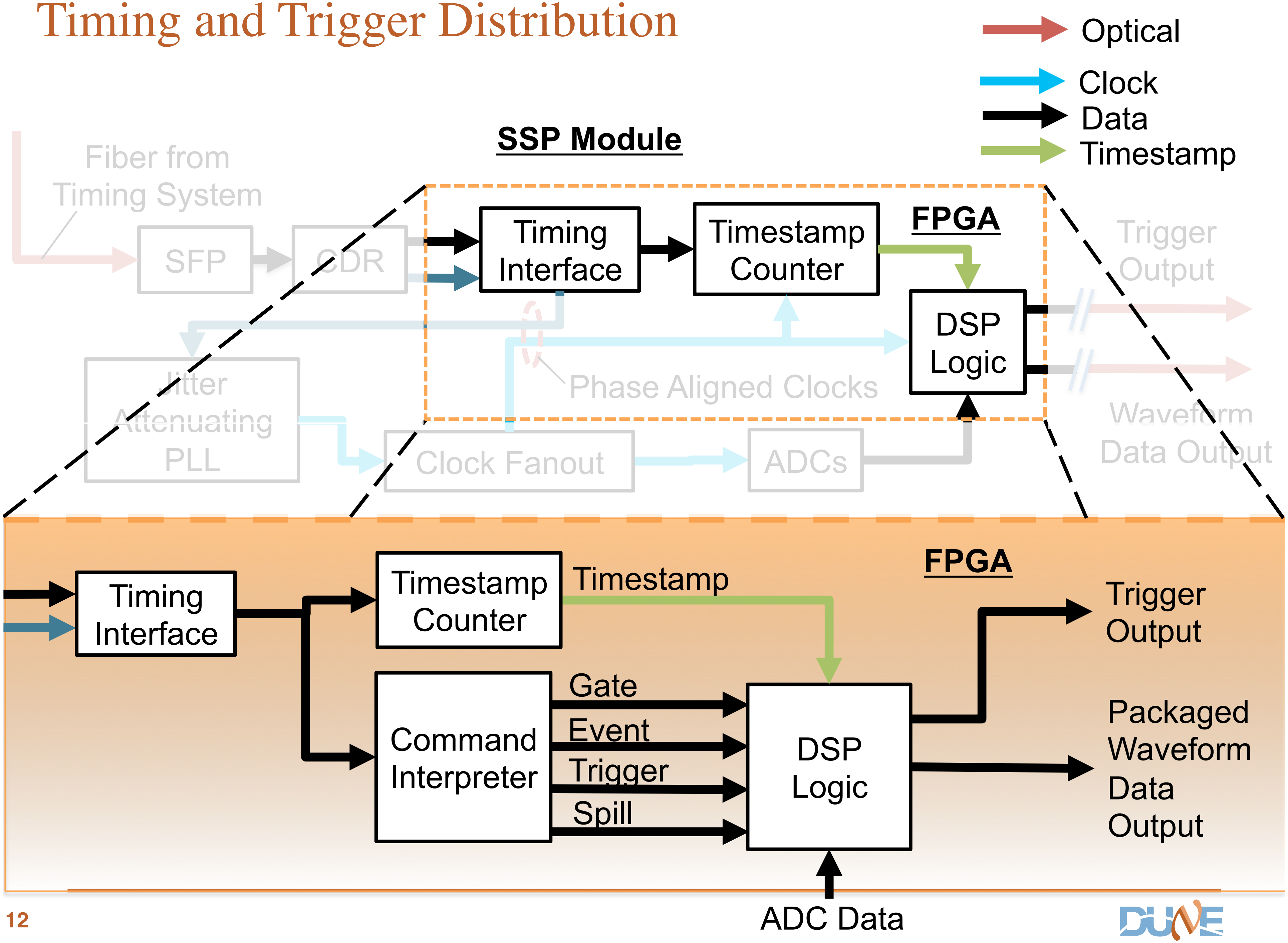
- Readout logic set to provide for different waveform readout lengths in-spill versus out-of-spill

- Self-trigger on cosmics and beam physics in ProtoDUNE case

Timing and Trigger Distribution



Timing and Trigger Distribution

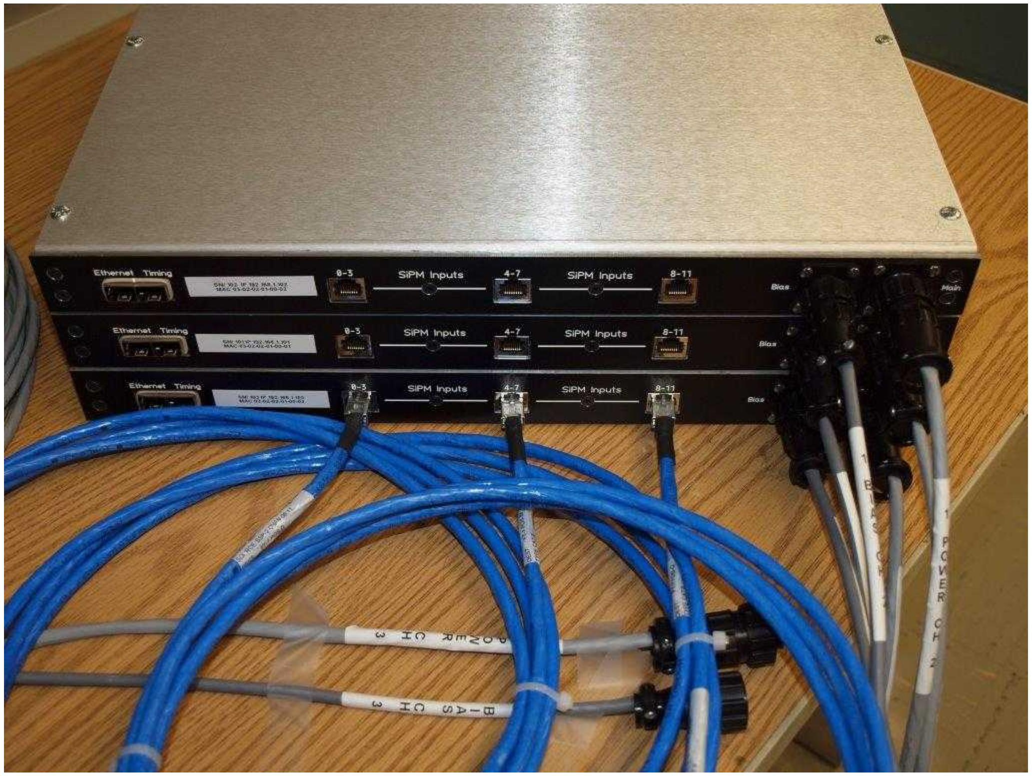


Overview of the ProtoDUNE SSP Module

- **The <u>S</u>ilicon Photo-multiplier <u>S</u>ignal <u>P</u>rocessor (SSP) prototype module:**
  - High-speed waveform digitizer
  - ***Current sensitive, differential input amplifiers***
  - Each channel has a ***14-bit, 150 MSPS ADC***
  - ***Timing*** obtained using signal processing techniques on leading edge of SiPM signal (CFD)
  - 12 channels per module
  - Uses Artix FPGA for sig. proc.
  - Has ProtoDUNE Trigger/Timing Optical Interface
  - ***Uses external floating DC power***
  - Has internal prog. SiPM bias (30V)
  - Trigger: self or external
  - ***Has Trigger Out signal via Optics***
  - Deep data buffering – 13 µS
  - ***No dead-time*** (up to 30 KHz/ch)
  - Programmable DAQ interface
  - ***Optical GbE communications***
  - Internal charge injection
  - Internal bias monitoring

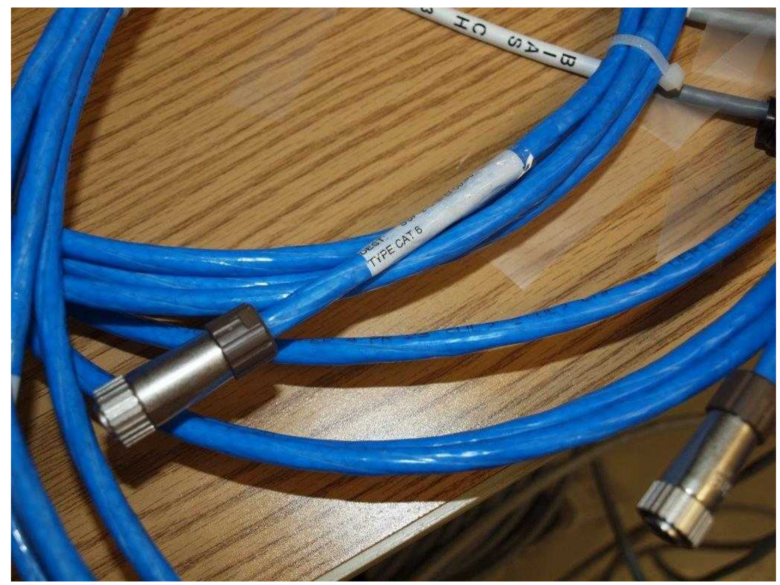
⇨ ***1U rack-mounted unit***

Overview of ProtoDUNE SSP (Cont.) - Signal Cables



Signal and power cables as connected to SSP
-Cat6 cables with RJ45 connectors on SSP side
-Bayonet connector on feedthru side

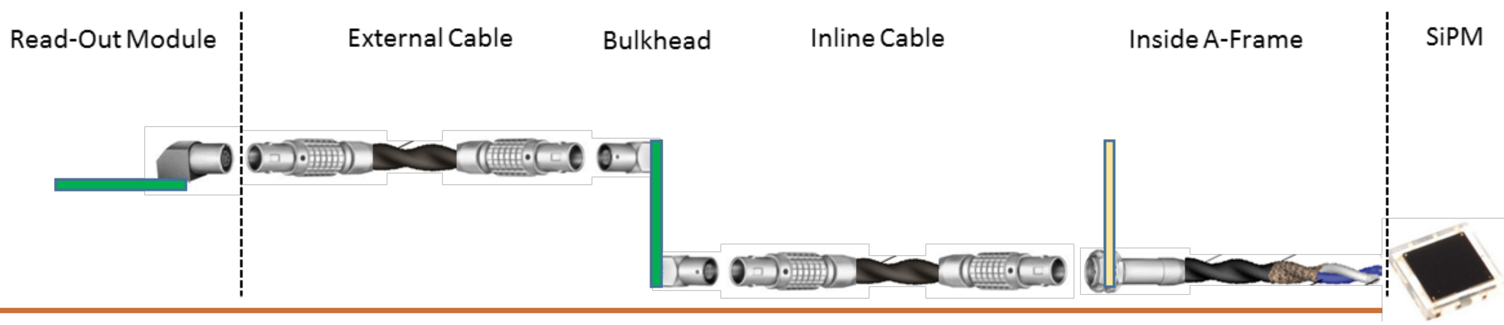
Flange/feedthrough end of signal cable. Signal cables labeled at both ends



Signal Cable Notes

Lessons learned from initial R&D (35t tests):

- **The initial readout system could easily digitize single pe waveforms over 20 m of cable**
  - No cold electronics needed, if cables of sufficient quality
- **The intrinsic noise performance in LAr is good**
  - ADC RMS values 2-3 ADC counts (120 – 200 nA) over 20 m of cable
- **The timing performance is good**
  - Timing resolution on single pe's ~2-3 nS over 20 m of cable
- **The internal bias & other features worked well**
- **The module was fairly robust, with few problems during operation (i.e. noise interference with TPC readout)**
- **Problems with the Cable Plant: The cables worked well, but…:**
  - The cables & connectors were expensive, difficult to fabricate, difficult to install
  - Have 240 SiPMs for ProtoDUNE, so much larger cable plant



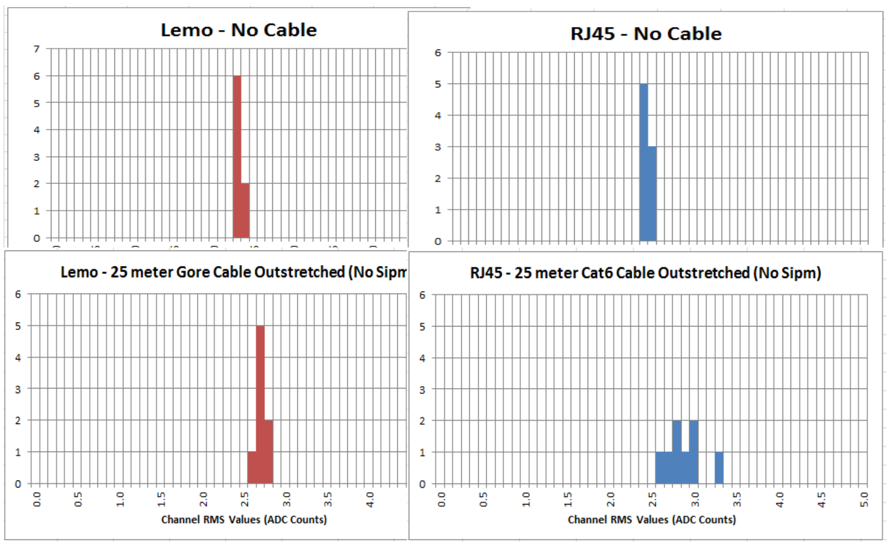
⇨ ***It is desirable to change this for ProtoDUNE***

Signal Cable Notes (Cont.)

- **Change Signal Cables & Connectors: decided to use CAT6 Cables**
  - -(4) individually-shielded, twisted pairs
  - -Mass-terminated, RJ45 Connectors on SiPM board & SSP; Possible alt. for Flange
  - -2 Cable Segments: Inside cryostat (”cryo” cables); Outside cryostat (“warm” cables)
  - -Estimated length: ~20 meters

  ⇨ ***SSP implemented with connector Daughter Board & appropriate back panel***

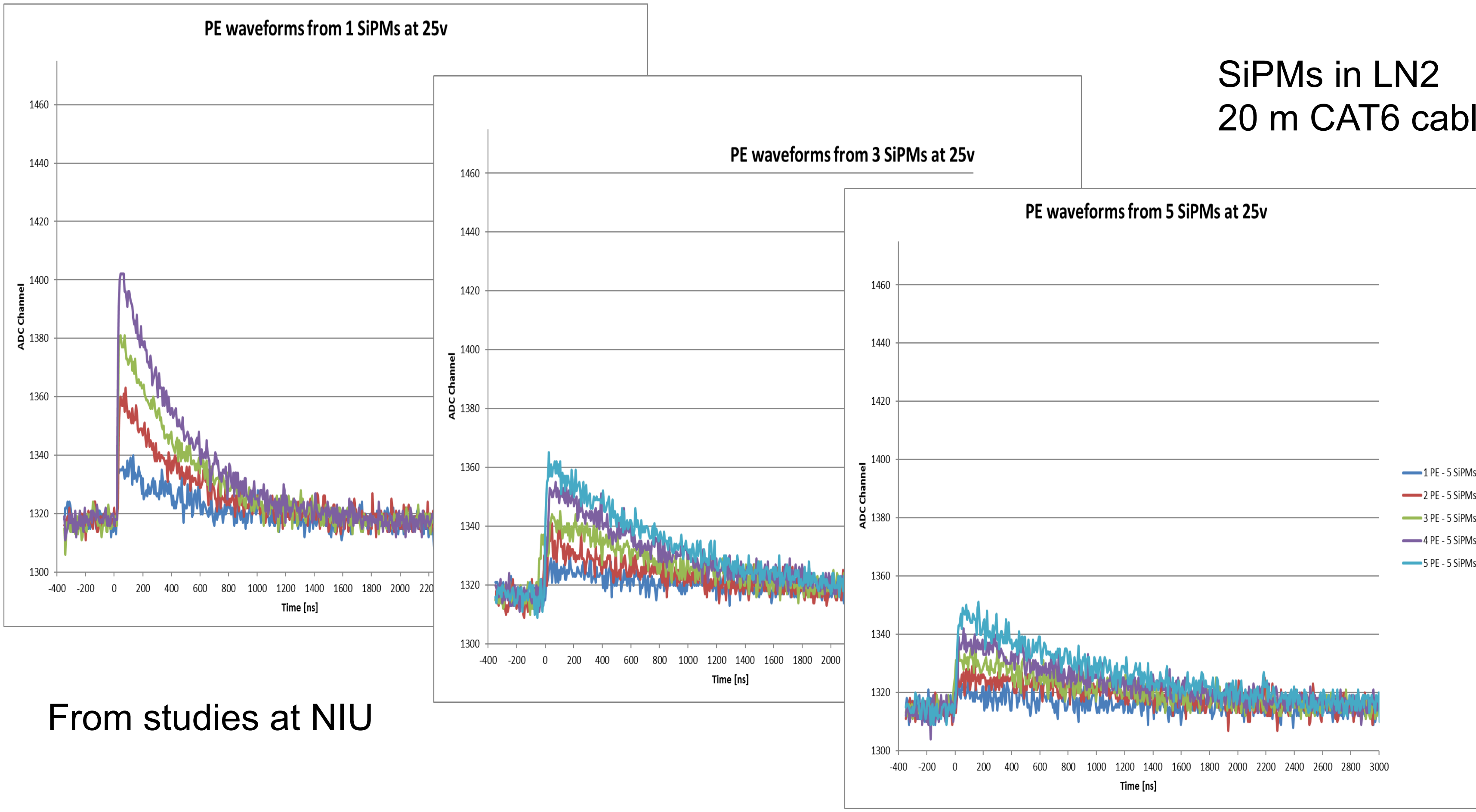
- **Compare performance of Gore Cables with CAT6 Cables**
  - -Measure pedestal noise with and without cables
  - -Compare the noise performance of the new and old cables



⇨ ***Significant saving in cost & ease of fabrication & installation***

SiPM Ganging Notes

- **Sum (3) SiPM outputs together**
  - Goal: further reduce cable plant costs & cable plant
- **Study: See reduced pulse height & longer tail as more SiPMs ganged together**



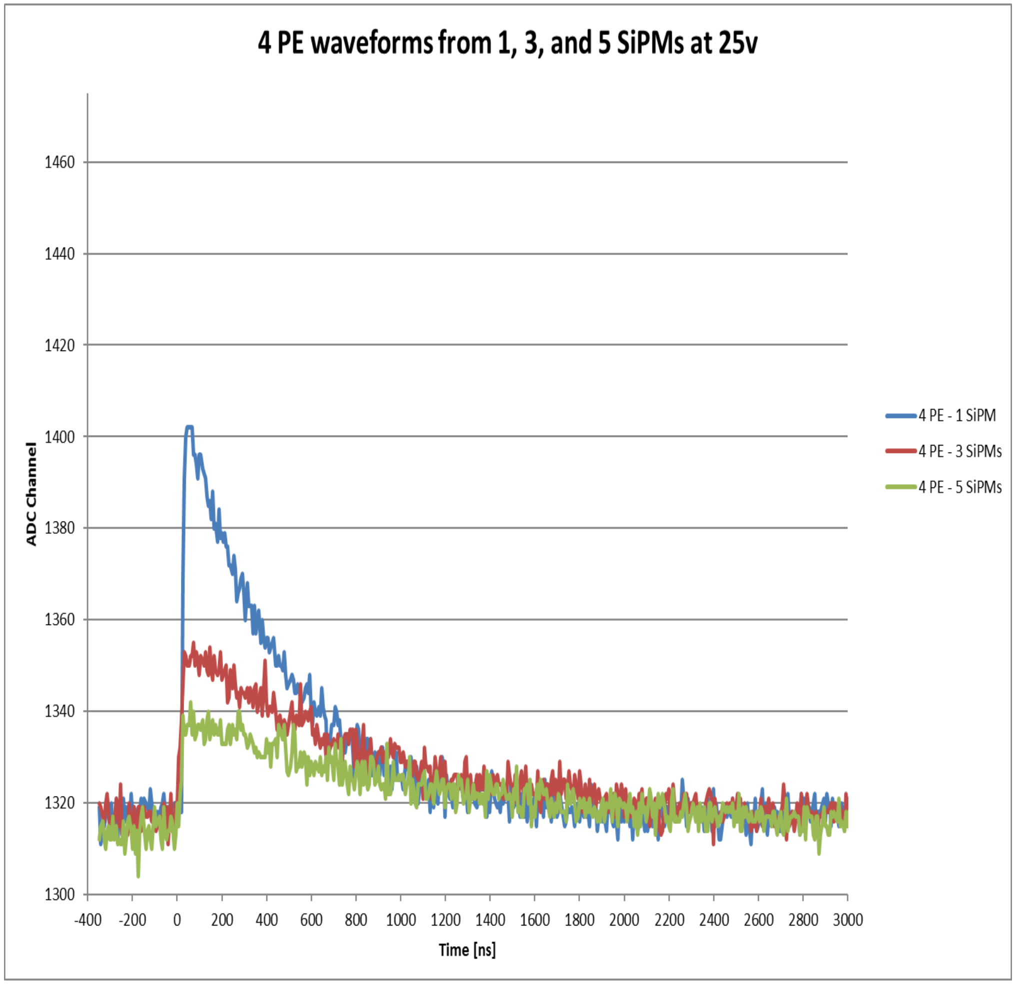
SiPMs in LN2
20 m CAT6 cable

From studies at NIU

⇨ ***Conclusion: Gang 3 SiPMs @ 25 meters should give adequate S/N, if environmental noise is low***

⇨ ***Marginal S/N if cables longer, or gang more SiPMs together***

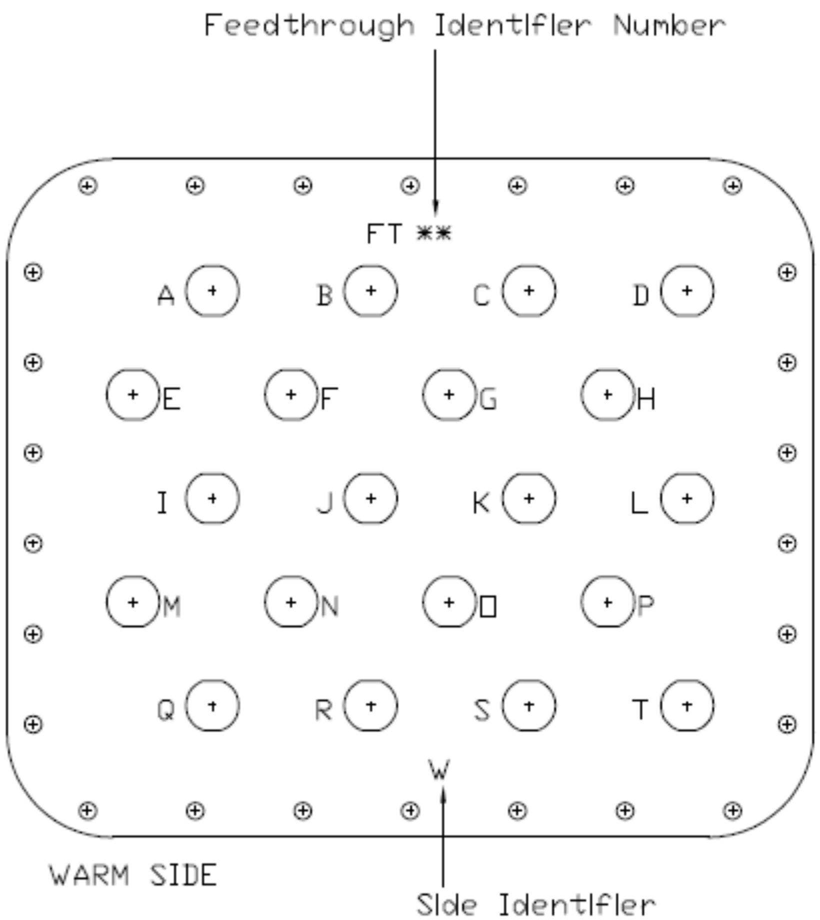
SiPM Ganging Notes (Cont.)

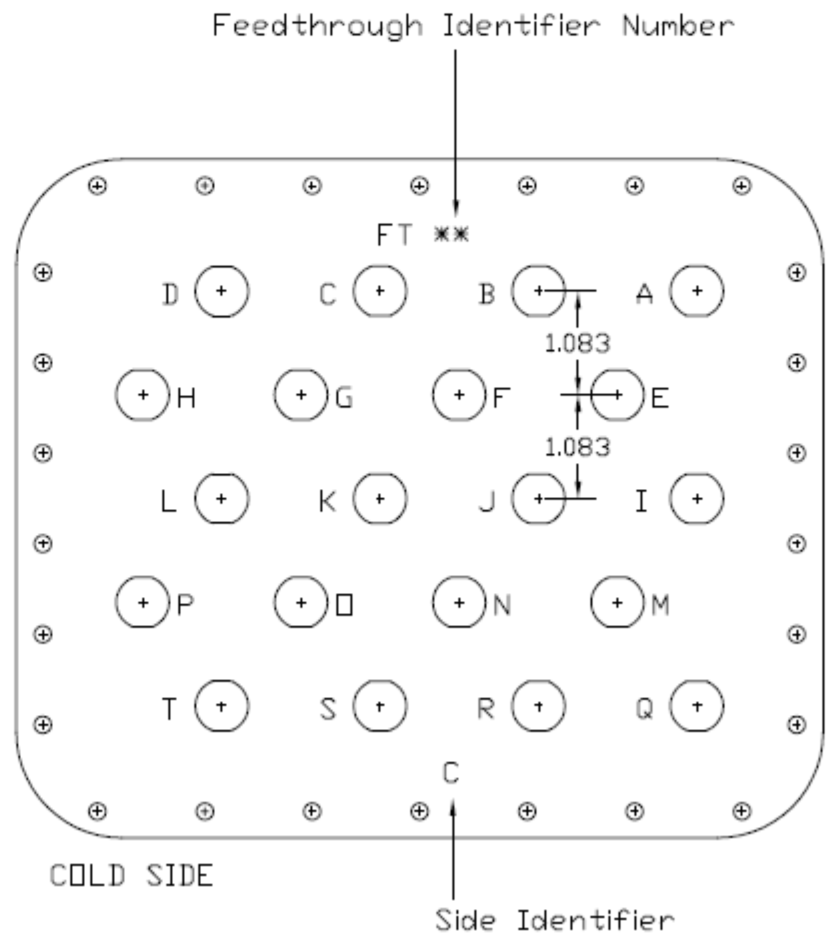


Test Condition	1 PE Peak (ADC Counts)	Decay Time (ns)
1 SiPM at 25v	16.8	560
3 SiPMs at 25v	10	1132
5 SiPMs at 25v	6.8	1172
5 SiPMs at 28v	10.2	1192

Photon Detector Signal Cable Feedthru

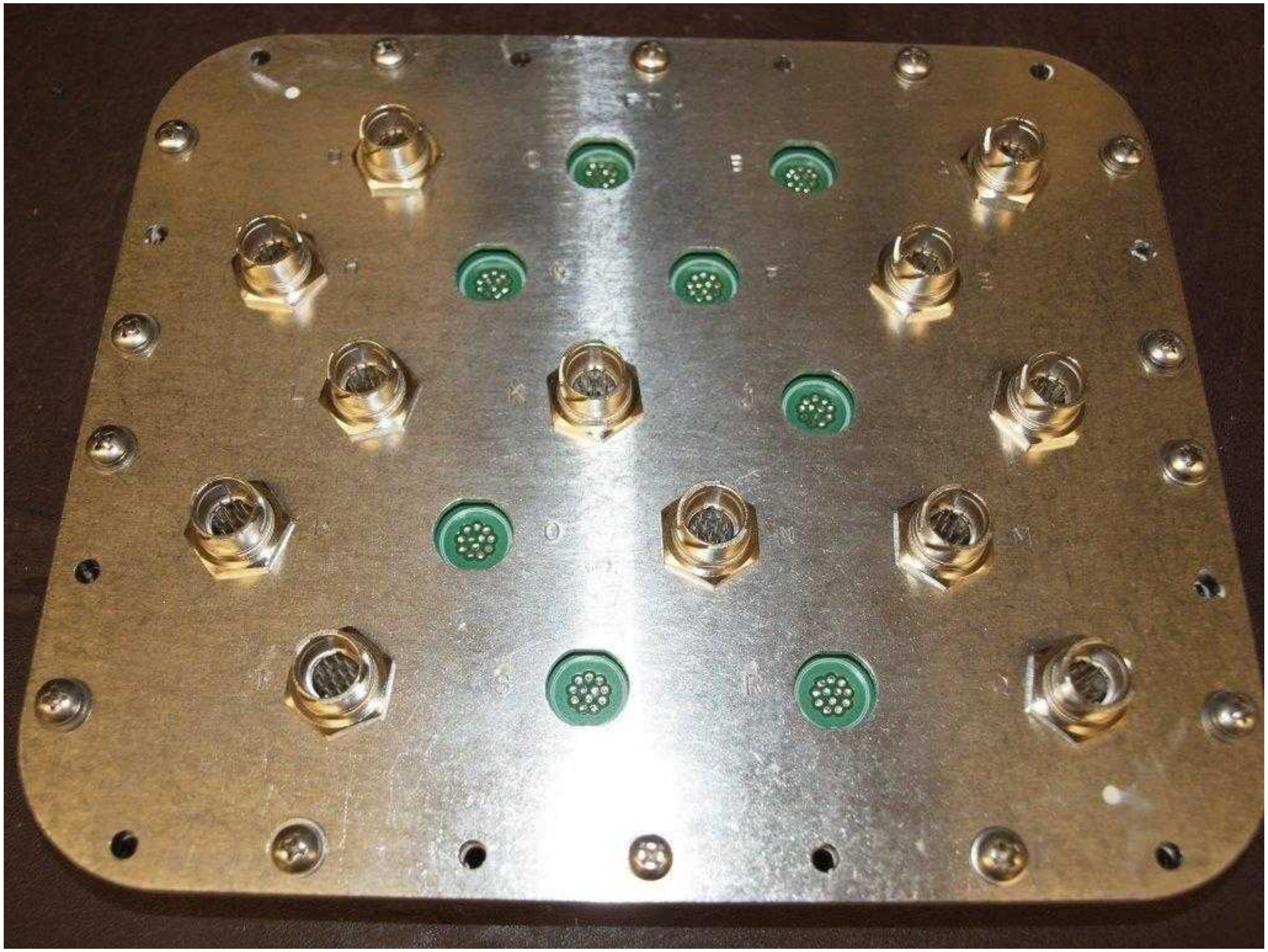
- Designed by ANL; integration in collaboration with ANL
- Drawings





Photon Detector Signal Cable Feedthru (Cont.)

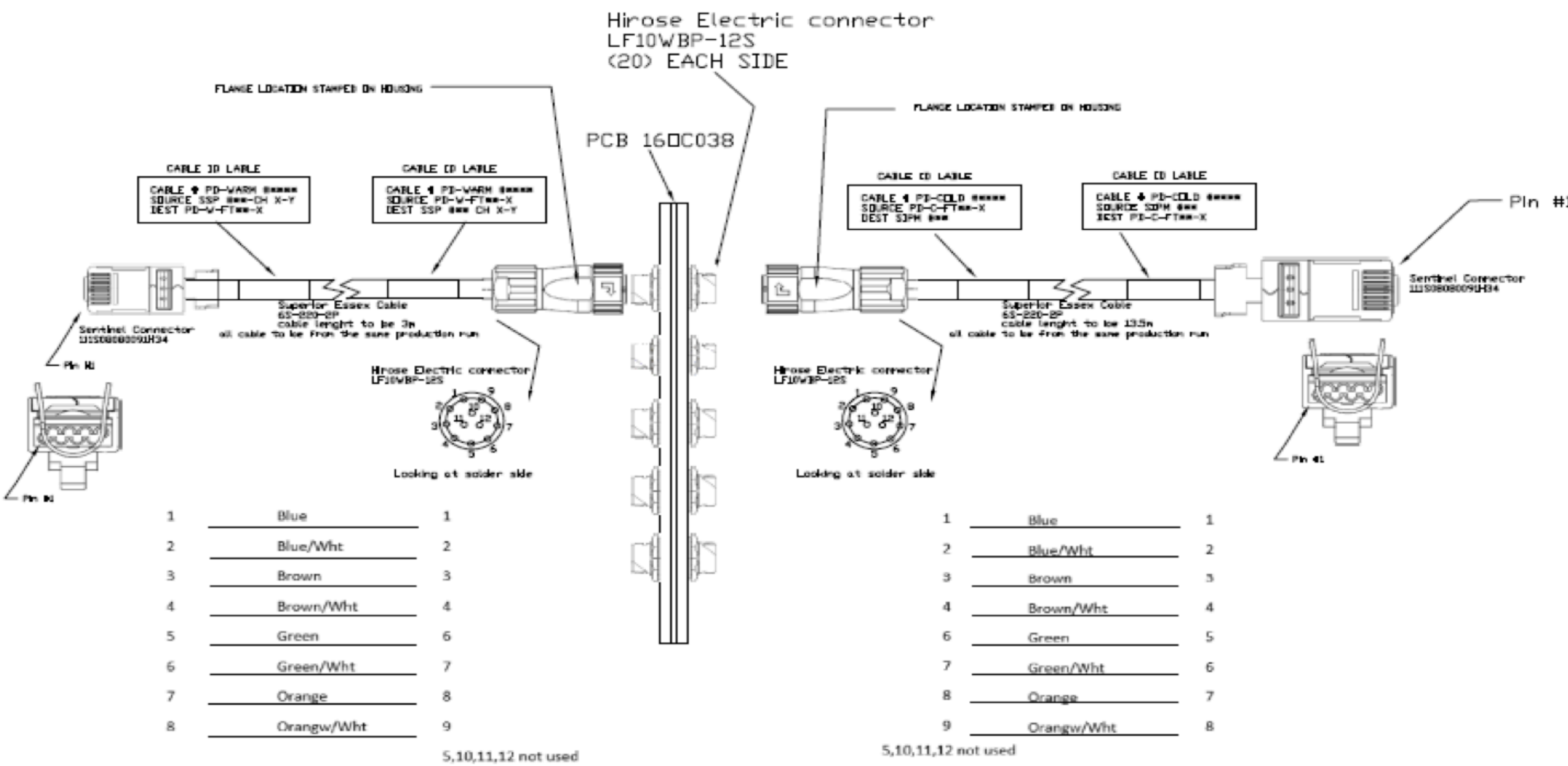
- Photo



PD Signal Cable/Connector Status

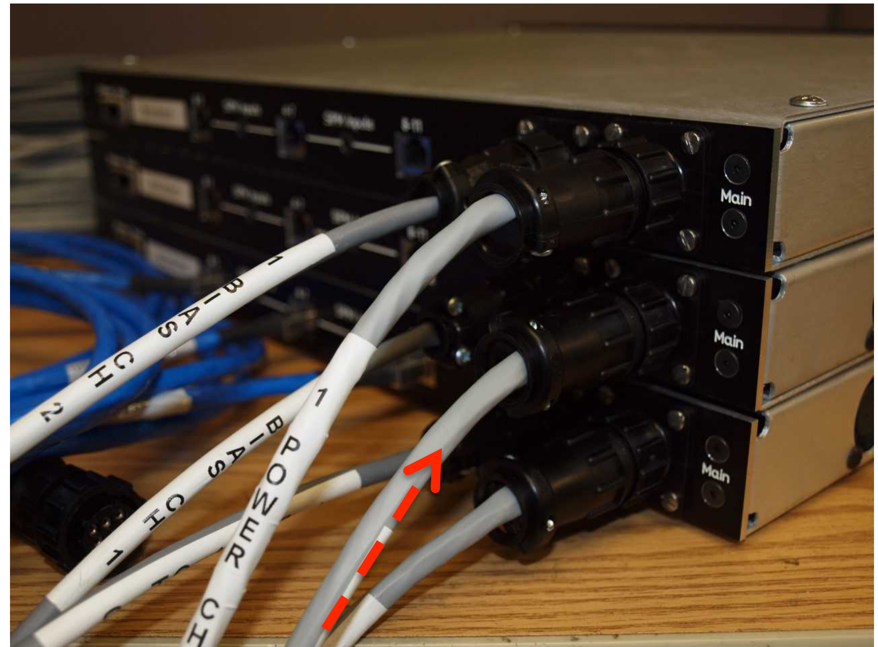
- The photon-detector signal cables for the first APA have been manufactured and delivered to CERN
  -passed electrical continuity tests at CERN

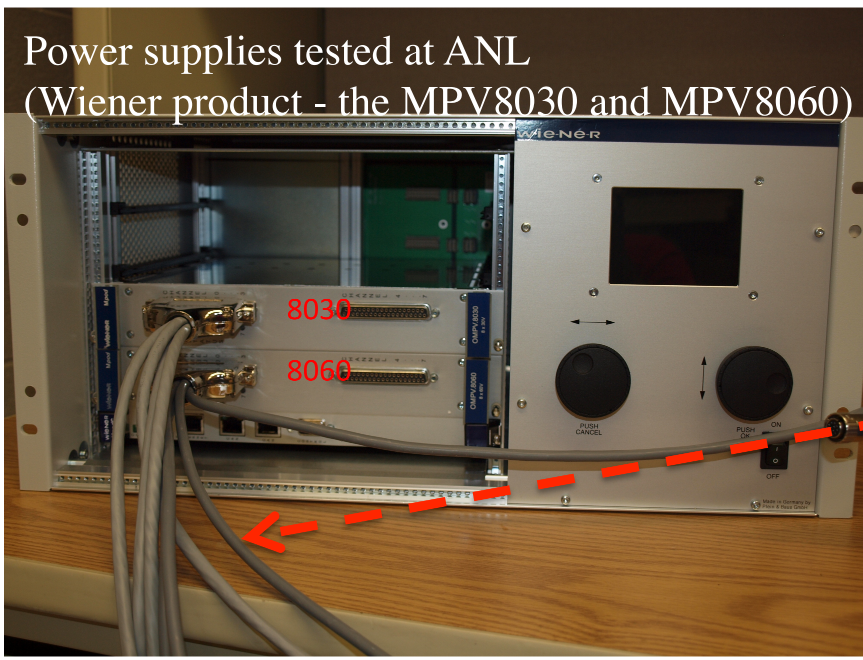
- Photon-detector warm and cold cables, and feed-through (labeling) scheme shown below:



Overview of ProtoDUNE SSP – Power/Bias

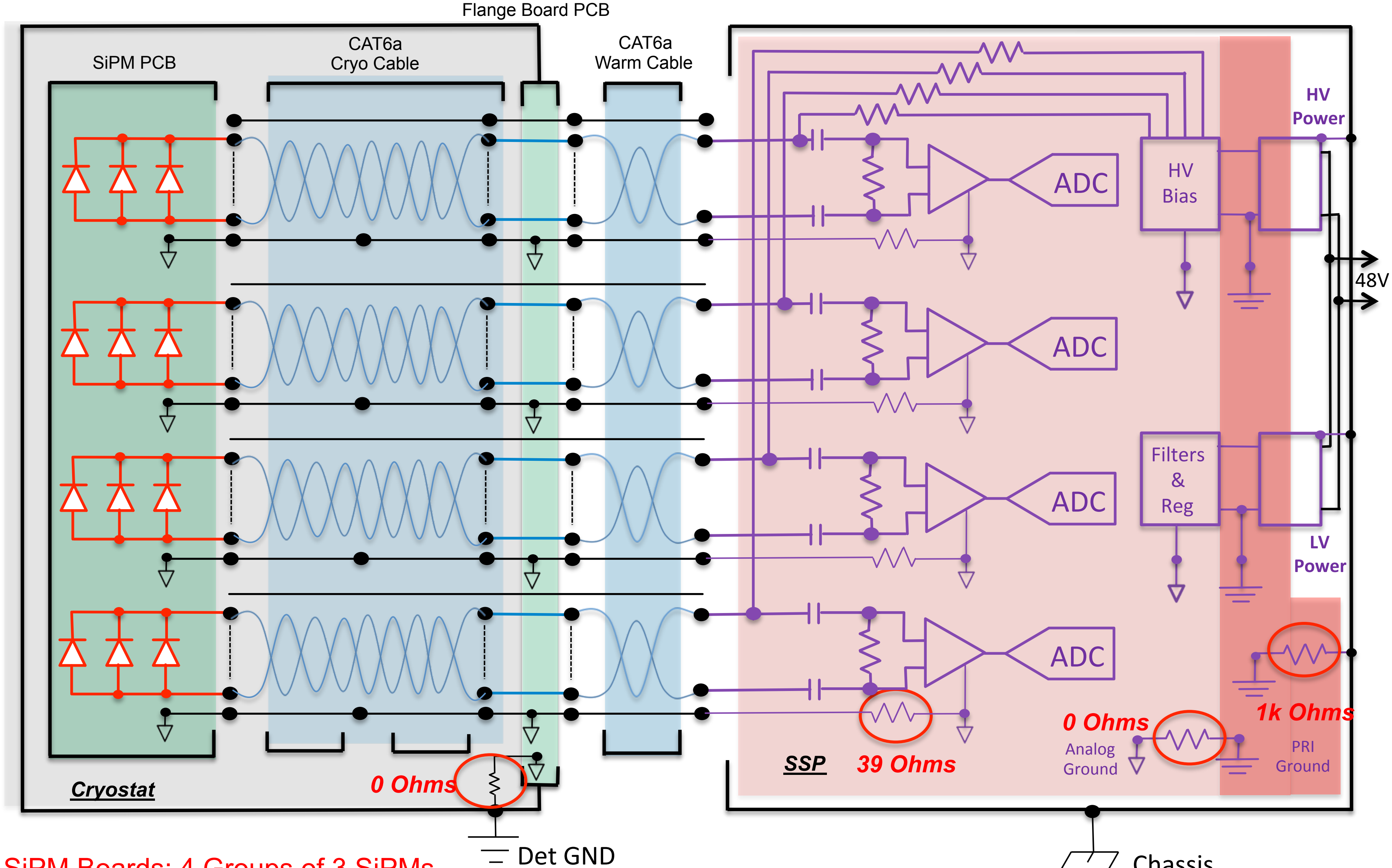
- SSP powered by DC power
  - -Bulk DC power and bias DC power supplied by Wiener commercial supply.
  - -0-30V/2.5A, 0-60V/1A
  - -SSP nominal draw 1.7 AMP
- Two cables (one bulk, one bias) connect a single power supply to four SSPs.





Two ends of same cables

SSP Grounding Plan for ProtoDUNE



SiPM Boards: 4 Groups of 3 SiPMs

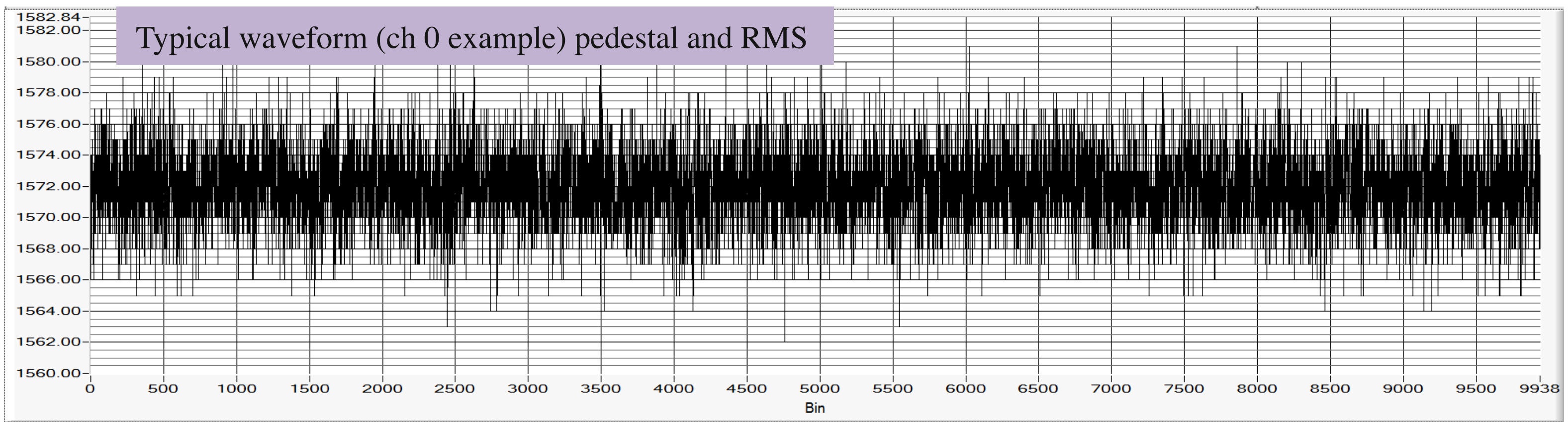
Signal Cables: 4 individually-Shielded Twisted Pairs

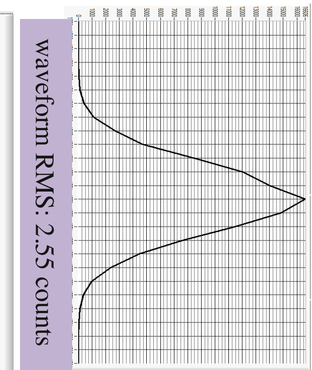
SSP Electronics (12 Ch per Module)

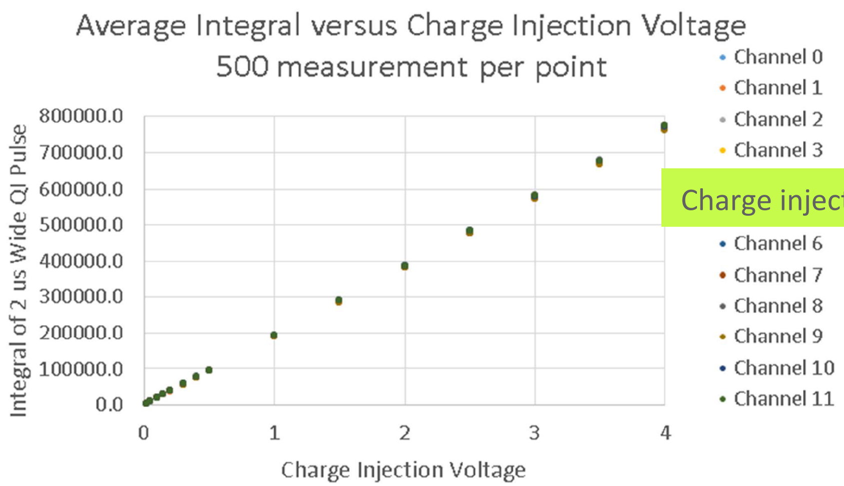
Summary of Design Choices to Mitigate Noise Risks

- With the need for long cables (~20 m) we have optimized front-end in the differential mode to enable common mode rejection. We have components with 0.1% tolerance in the differencing amplifier, which yielded ~35 db of rejection. . ***This helps reduce noise pickup on the signal cables for both internal and external sources.***
- We have tuned the ***bandwidth*** of the front end amplifier by optimizing the gain. This helps improve the bandwidth over the common mode range. ***This additionally helps reduce noise pickup on the signal cables for both internal and external sources.***
- We have added ***magnetic shielding*** over the switching power supplies in the SSP. ***This helps reduce noise pickup on the signal cables from noise generated by the SSP.***
- We have developed a ***grounding plan*** that uses a single point ground, defined to be at the cryostat. The front-end circuits are floating, and receive a ground reference when the signal cable is connected to the flange feed-through. ***This helps reduce noise from ground loops.***
- We have digital I/O to be all **fiber optic**, rather than a copper. ***This helps reduce noise pickup from external sources due to ground loops.***
- We have the ***powering scheme*** to use 16-30V DC input power with floating inputs, rather fhan 120V AC, with a safety ground. There are no longer any hazardous voltages in the SSP. ***This will help reduce noise pickup from external sources due to ground loops.***
- A special attention was payed to ***the termination of the signal cables*** in the SSP. ***This helps reduce the effect of noise pick-up from the TPC oscillations***

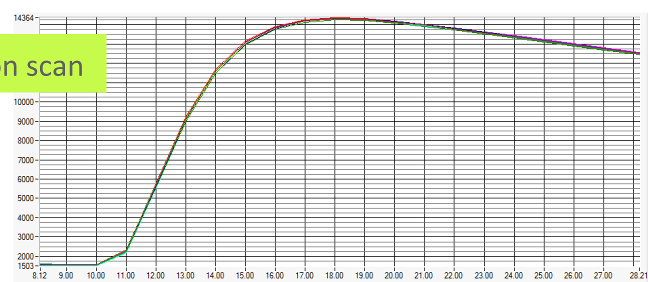
ProtoDUNE SSP Characterization Tests at ANL







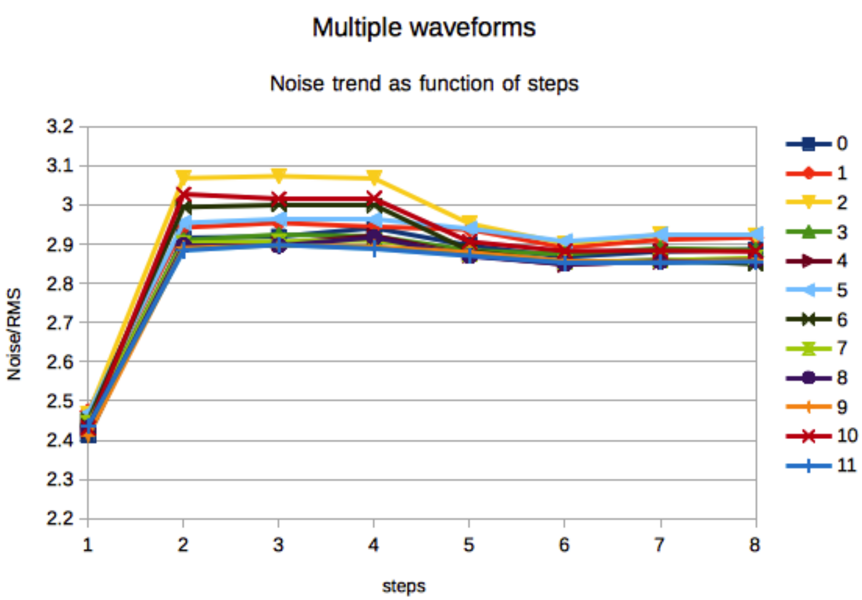
Charge injection scan



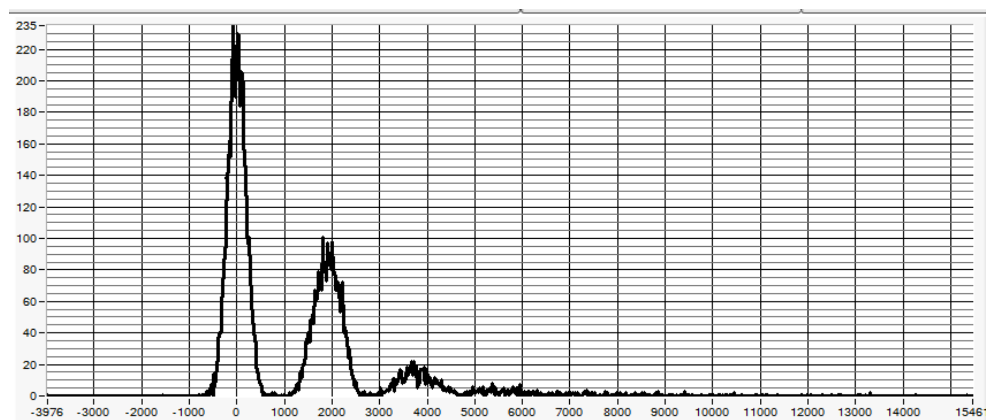
ProtoDUNE SSP Characterization Tests at ANL (Cont.)

- SSP Characterization studies were done to check a potential noise contribution due to each detector component (cables, flange, SiPM board) connected to the SSP cable inputs
- DUNEWare was used to look at individual waveforms, ADC counts for corresponding PEs, and PE energy peaks.
  - -For details see: Argonne-SSP Characterization Testing for ProtoDUNE-SP DUNE-doc-3126-v2

SiPM hoverboard in LN2 for testing SSP noise in cold



Waveform RMS in SSP as detector elements are added to readout in steps 1 to 8 (see docdb)



Integrated energy for 10K events collected with ProtoDUNE SSP. First peak is a pedestal, next is 1 PE, 2 PE peaks, etc.

ProtoDUNE SSP Characterization Tests at ANL (Cont.)

- SSP Characterization studies were done to check a potential noise contribution due to each detector component (c... flange, SiPM board) connected to the SSP cable input
- LBNE ... form counts ... aks.

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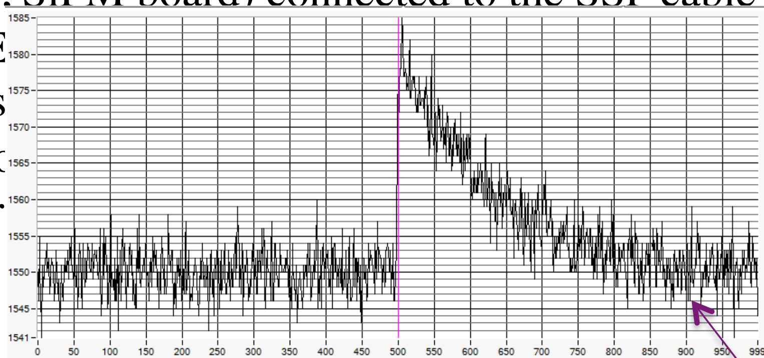
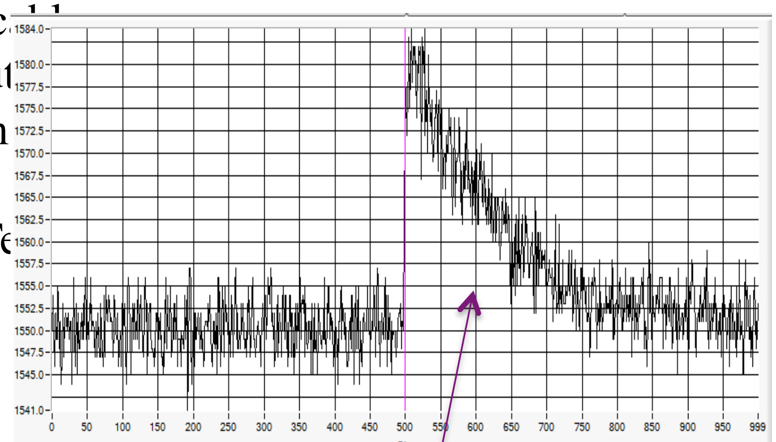
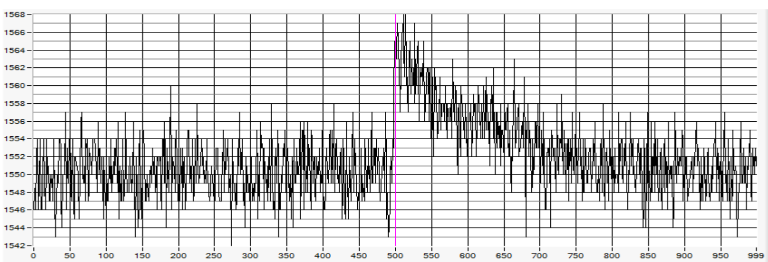
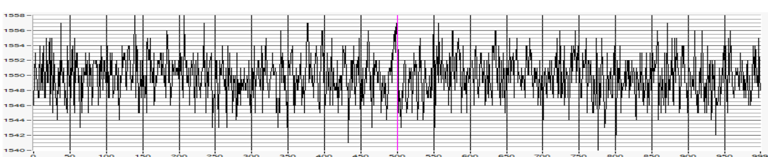
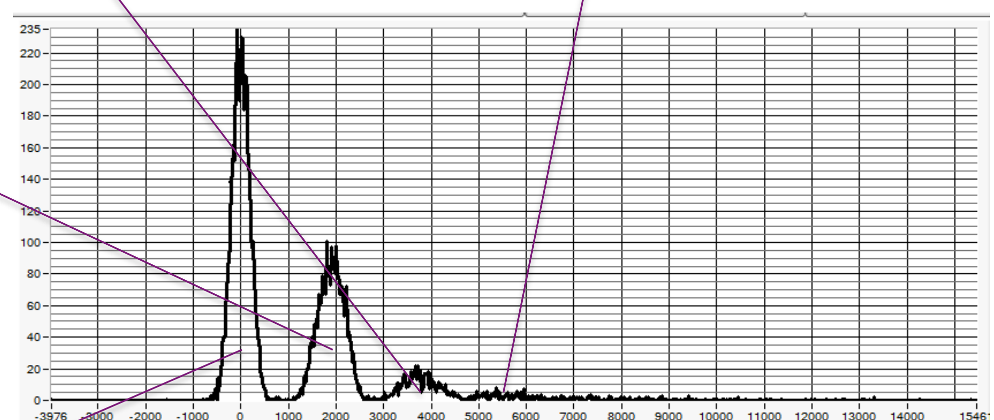






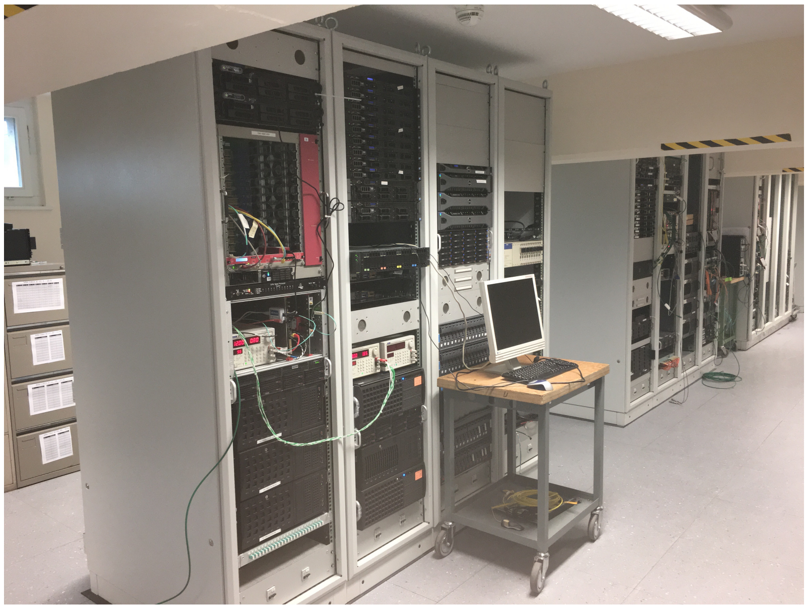




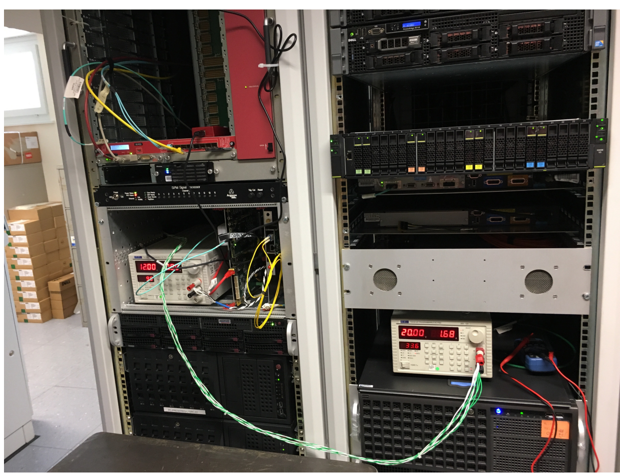
Integrated energy for 10K events collected with ProtoDUNE SSP. First peak is a pedestal, next is 1 PE, 2 PE peaks, etc.

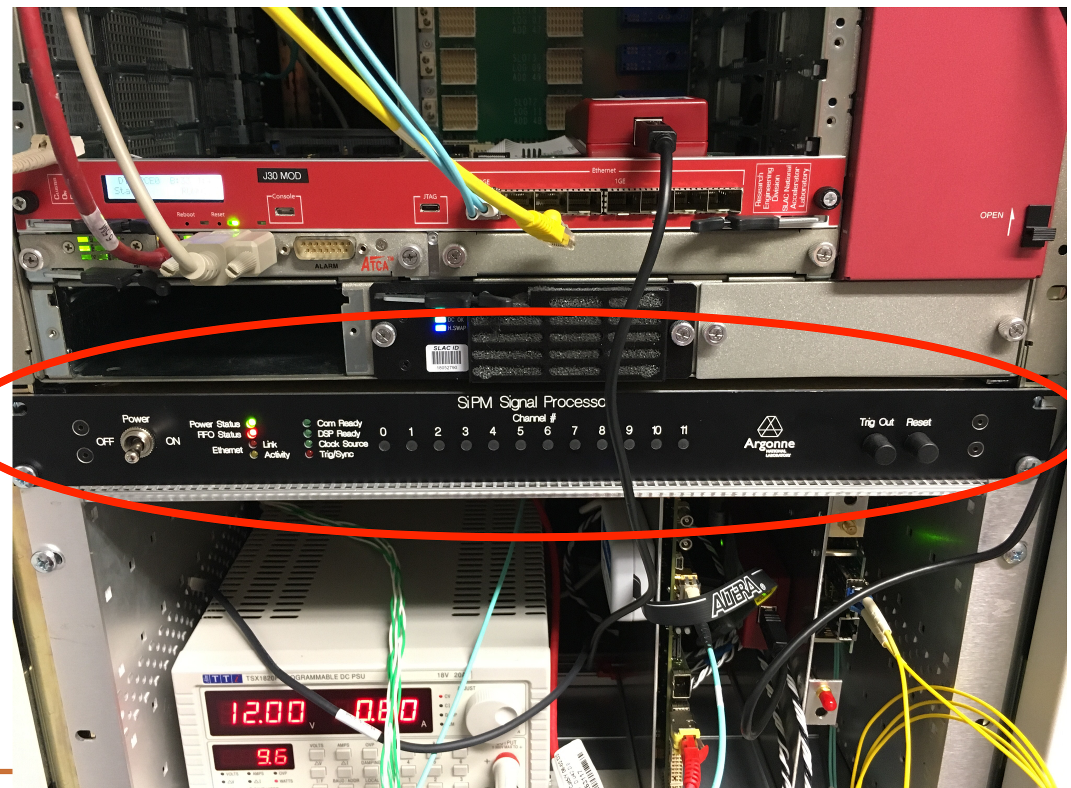
Test at CERN: ProtoDUNE SSP tests at CERN

- We delivered two ProtoDUNE Photon Readout Boards (SSP) to CERN by now:
  - -First SSP (prototype) delivered ProtoDUNE Vertical Slice DAQ setup May 8 – 14, 2017.
  - -First SSP from small-production for ProtoDUNE Integration Tests delivered July 13, 2017.



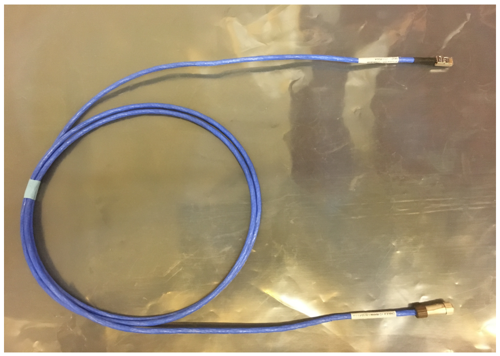
First SSP at ProtoDUNE Vertical Slice DAQ setup May 8 – 14, 2017
-trigger, timing, DAQ tests successful





Tests at CERN: PD Signal Cable/Connector Status

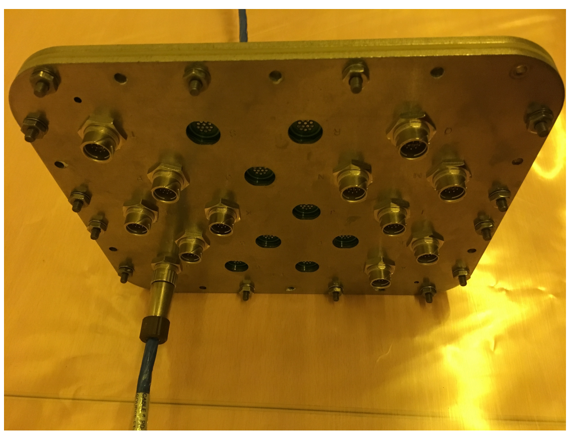
- Example of a warm cable.
  -Middle: RJ45 connector to be attached to the readout board (SSP).
  -Right: Circular connectors (LF10WBP-12S) on a warm side of PD feed-through.

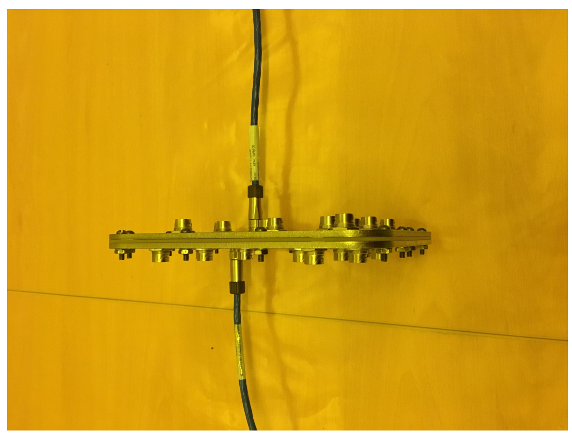


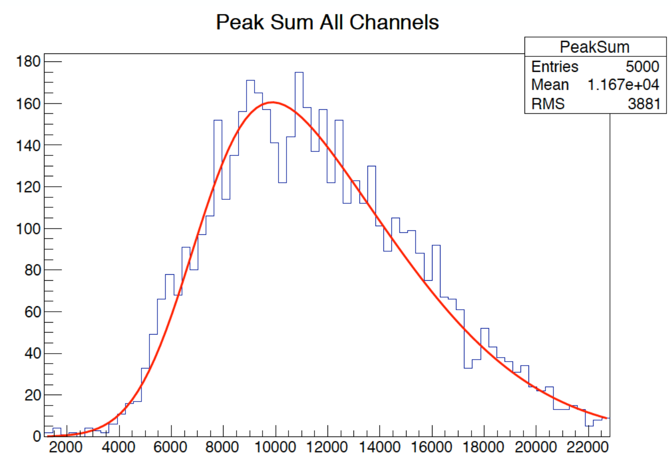

- Example of a cold cable.
  -Middle: RJ45 connector to be attached to the SiPM hover-board.
  -Right: Circular connectors (LF10WBP-12S) on cold side of PD feed-through.


Tests at CERN: PD Cable/Connector and Signal Feed-Thru

- First feed-through for the Cold Box has been delivered to CERN
- Performed Electrical Signal Tests in ProtoDUNE clean-room with
  - -"cold" signal cables
  - -"warm" signal cables
  - -signal feed-trough
- Put together a setup with the dark box, photon-detector, UV LED + pulser, photon-detector readout board (old type SSP) + PC, photon-detector signal cables, and the photon-detector feed-through.
- Test successful for all cables/feed-through channels: clear signals observed.





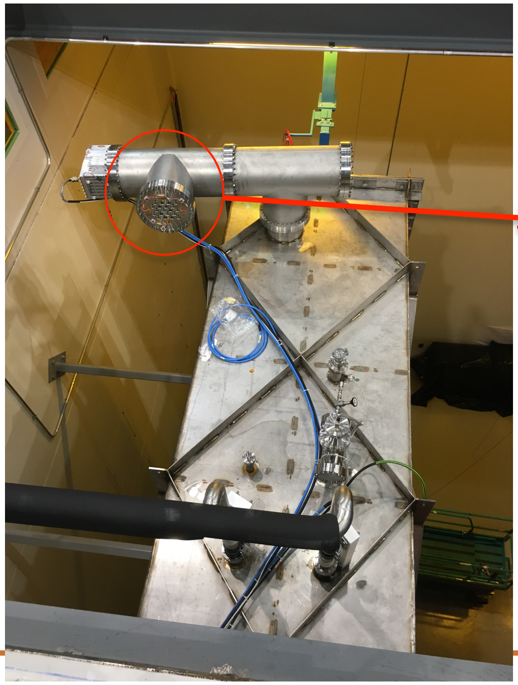


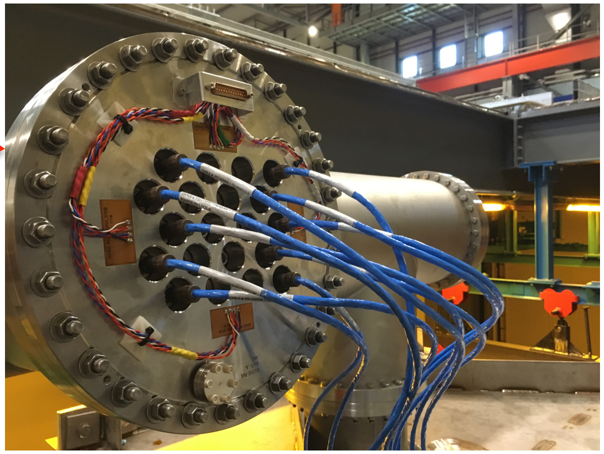
Typical distribution of ADC counts from 5000 integrated waveforms

Tests at CERN: ProtoDUNE APA 1 in the Cold Box

- APA #1 is inserted into the cold box
  - -The APA included 10 photon-detectors each with four twisted-pair cable for readout.
  - -Total number of photon-detector readout channels is 40.
  - -Photon detector installation into APA completed in August.

- Cold photon-detector cables have been connected to photon-detector signal feed-thru.
  - -The feed-thru is fabricated at ANL, but has been installed on the signal flange by BNL team who actually designed the flange.

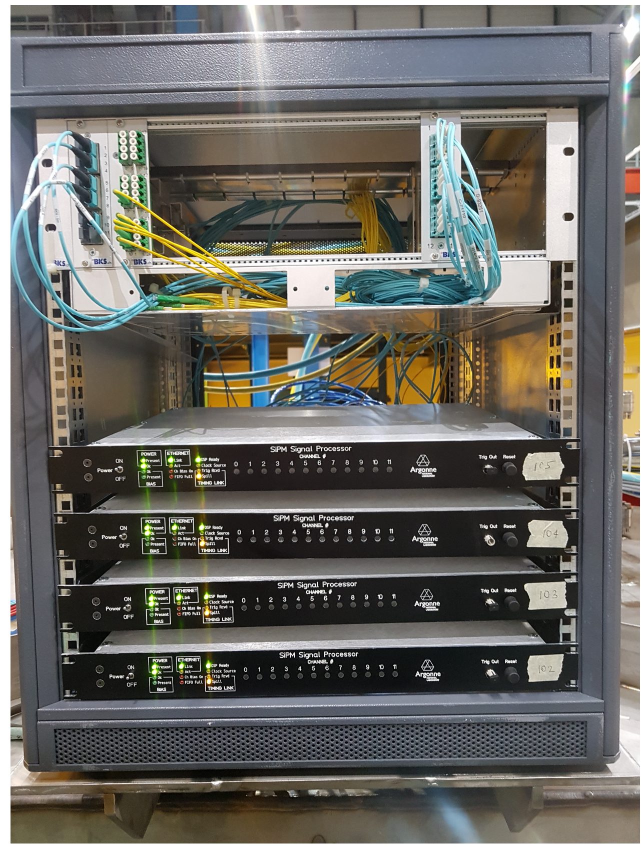




- Warm signal cables have been connected to outer side of photon feed-thru on October 16
  - -pictures show the photon feed-thru before and after warm cable installation
  - -a diode test of the cable/feedthru connectivity to SiPM has been conducted

Some Additional Pictures

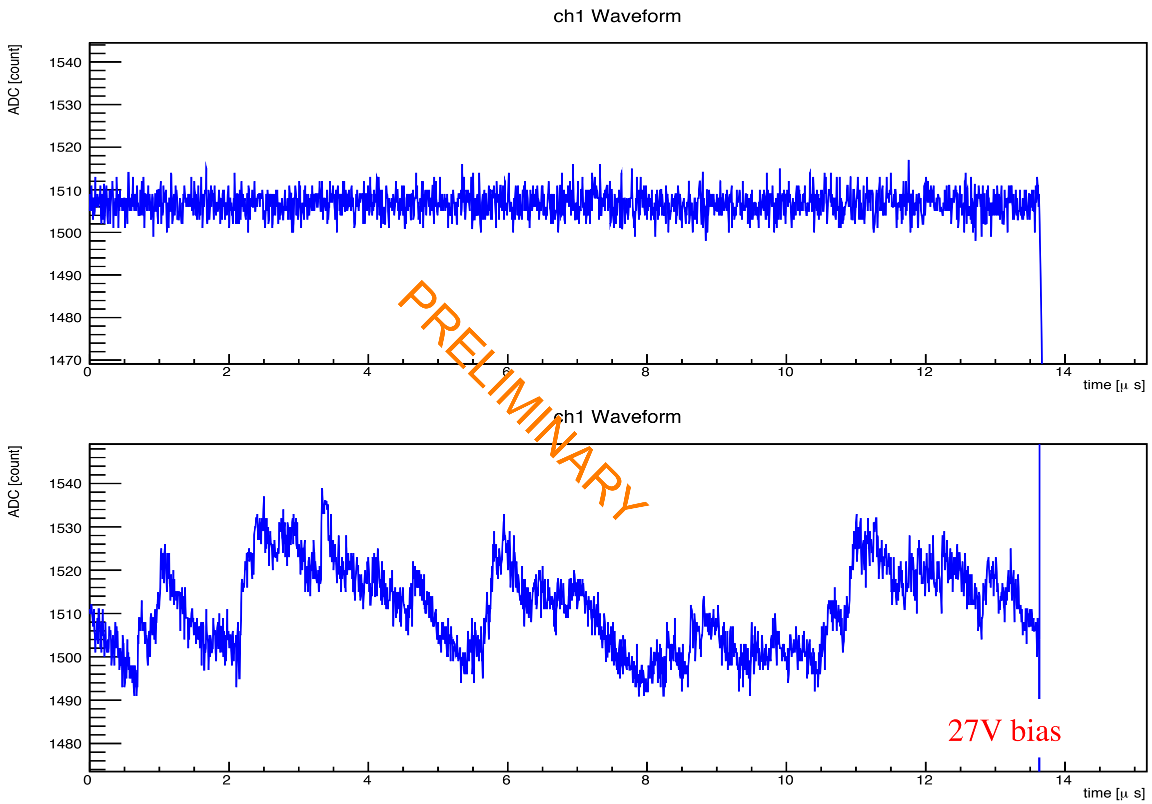
- Timing/Trigger and DAQ readout optical connections installed through patch panel
  - -Photon-Detector optical fibers attached to the readout back-end



- Crate for PD readout boards installed on the top of cold box
  - -Photon-Detector signal cables attached to the readout back-end
  - -Power cables form remote power supplies routed and connected to the readout back-end

Initial DAQ Readout Test

- Performed initial readout tests connecting a laptop to readout boards
  - -Confirmed all channels are connected
  - -Checked baseline for each channel (no SiPM bias). Found Expected ~3 ADC counts baseline RMS.
  - -Checked warm SiPM response (with SiPM bias)

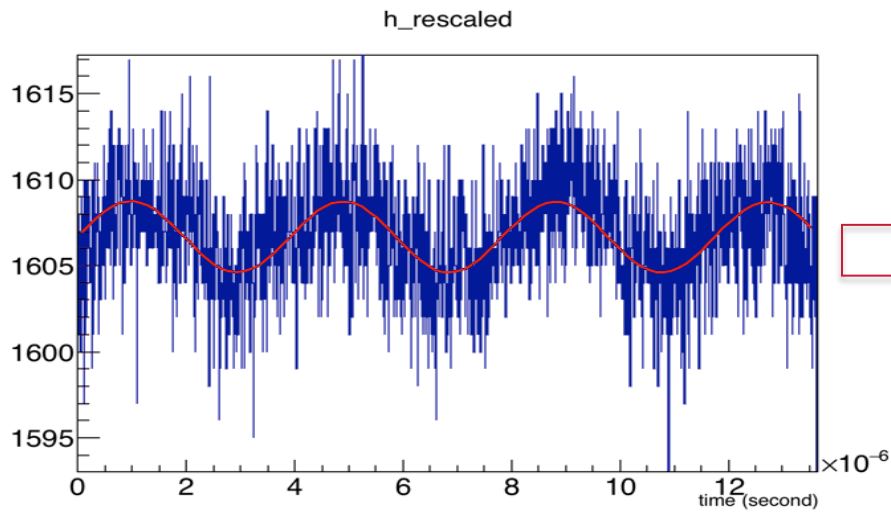


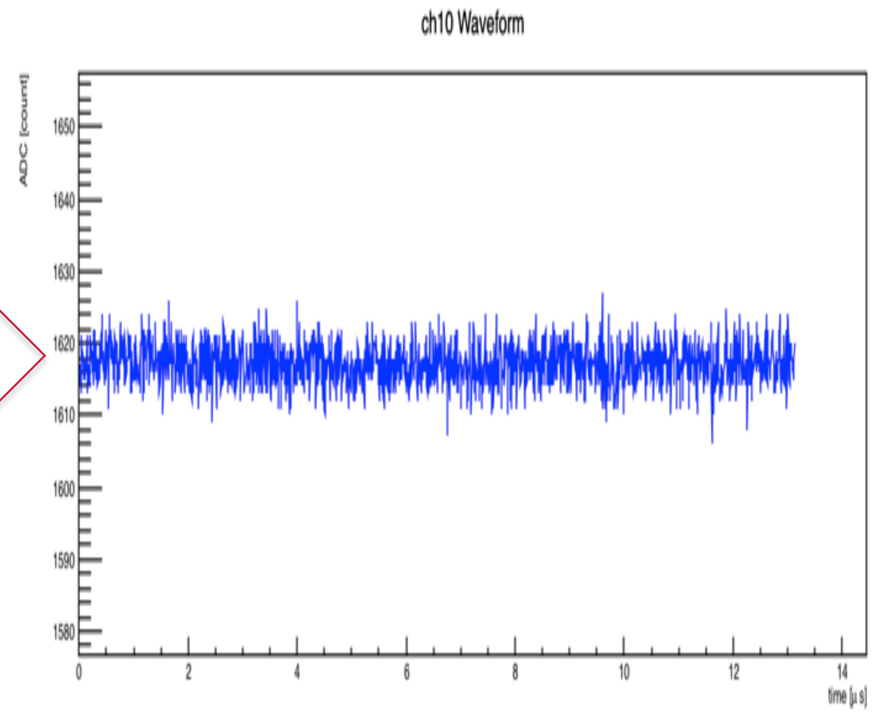
- A typical warm SiPM response has been observed with all 40 photon-detector channels in the “warm” Cold Box

Initial DAQ Readout Test

- Performed tests looking for a noise
  -In joint run with CE (one WIB used) we found CE readout did not see anything coming from PDS

- Biased one board at the time below break-thru voltage (ie 20-25 V)
  -Found indication of ~250 KHz noise at ~2-4 count level.

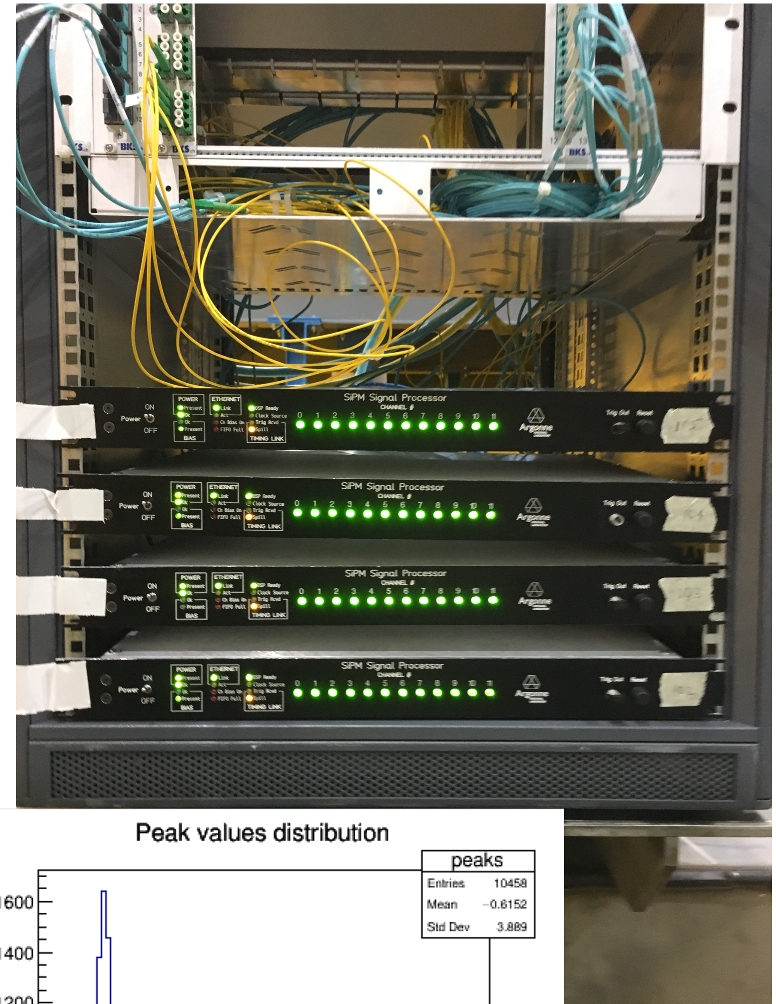




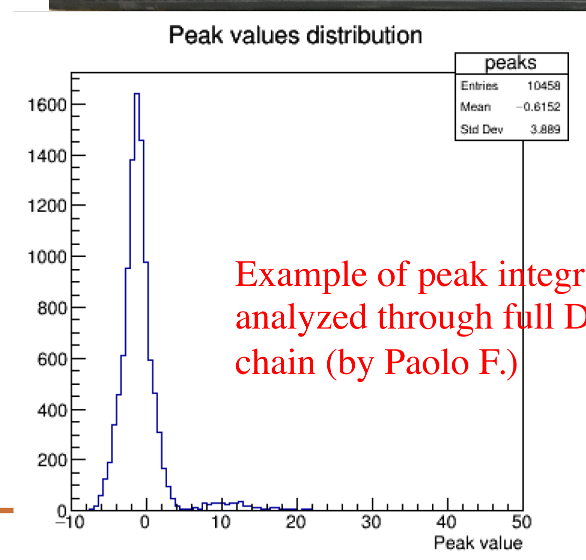
- However this was studied and understood as the grounding problem ***=> noise is now gone!***

Full ProtoDUNE DAQ Readout Test

- DAQ connectivity tested with new optical cables and with a modified network configuration
  - -For cod box operation assigned new network switch by CERN IT
- DAQ was able to perform a full readout of unbiased photon-detector system as of October 20. Credits to J. Haigh.
  - -Picture on the right shows front-end indicators responding to DAQ commands
  - -One of the first DAQ reports (by J. Freeman) is shown below



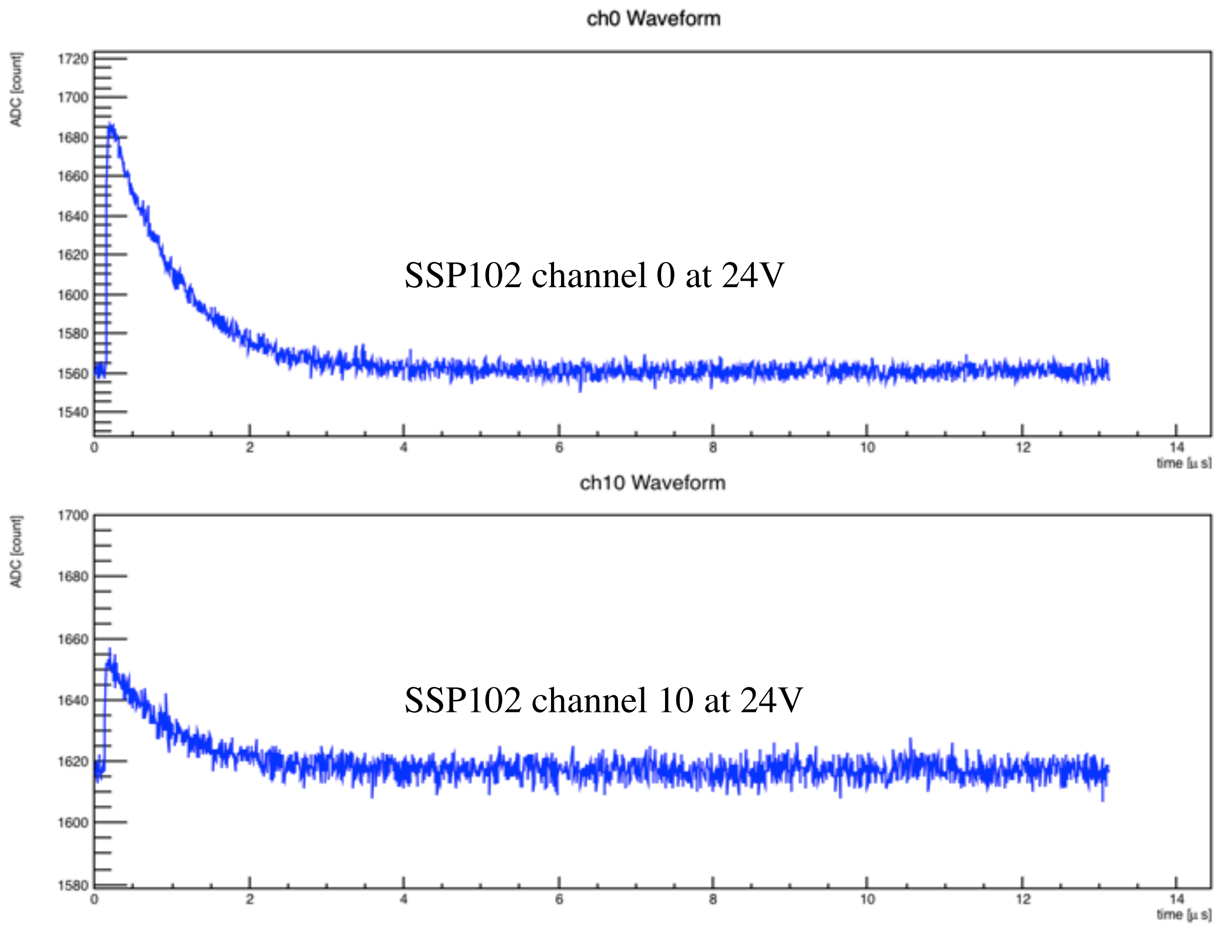
Subject: Run 1000288
Smooth, error-free run with 4 SSP's and timing
Run at 6 Hz
Run number: 1000288
Start time: Sat Oct 21 17:39:06 UTC 2017
Stop time: Sat Oct 21 18:21:51 UTC 2017
Configuration: Coldbox00003
DAQ directory: /nfs/sw/artdaq
Device: DataLogger at np04-srv-014
Device: EventBuilder at np04-srv-014
Device: timing at np04-srv-012
Device: ssp00 at np04-srv-012
Device: ssp01 at np04-srv-012
Device: ssp02 at np04-srv-012
Device: ssp03 at np04-srv-012
Run lasted for about 43 minutes before I stopped it.



Example of peak integral analyzed through full DAQ chain (by Paolo F.)

More Recent “cold” Cold Box Tests

- Clean waveforms are found in the data when triggering above noise RMS level
  -example at 24V, trigger threshold at 30 ADC counts



- Tests with UV LED on/off: analysis underway

DUNE Far Detector Photon-Detection R&D (slide from DAQ talk*)

- Going from ProtoDUNE to DUNE
  - -New readout architecture is not defined
  - -Just started within new Photon-Detector SP Consortium

- Photon–Detection R&D is ongoing in several areas
  - -Type of photon collector (acrylic bars, ARAPUCAs, wave-length shifter …)
  - -Type of photo-sensor (Sensl, Hamamatsu, …)
  - -SiPM ganging scheme (passive, active, number of SiPMs)
  - -Cable type and Feed-thru designs
  - -Number of readout channels?
  - -Prompt vs delayed light?
  - -Physics Simulation to refine physics requirements

- Readout Electronics
  - -Options include waveform digitization, charge integration, hybrid solutions
    - => Don't want read out full waveforms (data storage, bandwidth issues)
      Need to optimize sampling rate, for timing resolution and peak finding, and pipeline depth
- The DAQ interface system for ProtoDUNE is scalable to DUNE
  (put aside the fact we don't know what readout architecture will be)

Optimizing the Photon Detector Readout for DUNE

- Cold front-end
  - Probably will want cold summing amplifiers on the front-end
    - We believe that we are at the practical limit for S/N with passively summing 3 SiPMs together
    - Likely will want to increase this (Arapuca…)
    - Put gain at front-end to improve S/N, & drive cables

- Unless there is additional R&D, probably elect to continue to use warm digitizers
  - Simple
  - Low-risk
  - Higher reliability
  - Easy access and maintenance
  - Reduced heat and power problems in the cryostat
  - Reduced infrastructure requirements
  - Reduced digital noise in cryostat

Optimizing the Photon Detector Readout for DUNE (Cont.)

- Requirements & Features for Warm Digitizers
  - Low cost (target < $100/ch)
  - Higher channel density per module (12 ch now → 64 – 128 ch)
  - Digitizer requirements
    - Multi-channel
    - 14-bit minimum
    - Sampling rate?
      - 150 MSPS now gives ~3 nS timing resolution in lab tests
      - Slower sampling → lower timing resolution, but maybe OK…
    - Semi-custom ASIC? (ultrasound chips)
    - Custom ASIC? → potentially expensive R&D
  - Provide bias voltage for SiPMs
    - Control each channel separately?
    - Current & voltage monitoring?
  - Need differential receiver amplifiers with high CMRR (difficult…)
  - Charge Injection/diagnostics
  - Interface to DAQ (Fiber, 10 Gbps?)
  - Interface to Timing System
  - Powered by DC voltage? (no AC?)

Summary

- Design of SSP is mature
  - -We manufactured devices for Integration effort at CERN.
  - -Tests at ANL and at CERN met expectations.
  - -Tested with the Cold Box
  - -Integrated with DAQ Interfaces (Timing, trigger, readout)

- Specification and design documents in a good shape; fabrication procedures stable and clearly documented.

- Testing procedures understood, conversion to automated procedures in progress, on schedule for use in production run.
  - -*We are ready to go with the full production*
  - -*Will integrate ARAPUCA design with the readout*

- Plan to use these results and expertise to go from ProtoDUNE to DUNE