The DUNE Single Phase Photon Detection System

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NNN19

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UNIVERSITY OF MICHIGAN

DUNE

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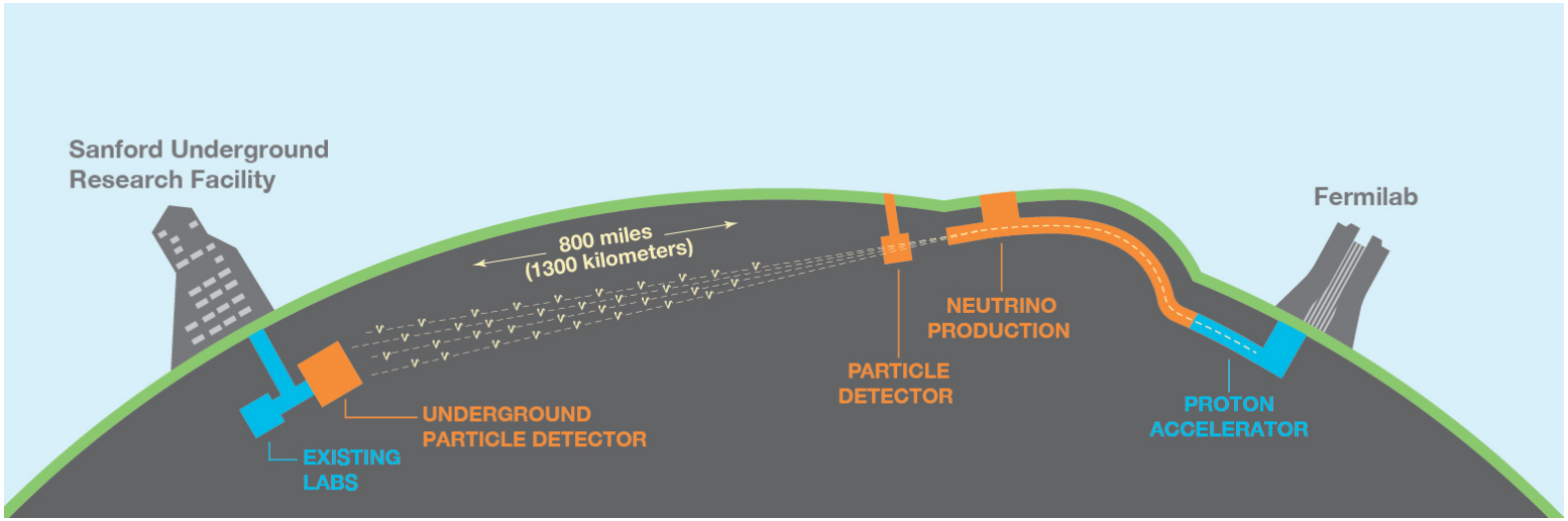


- **Neutrino oscillation physics:** neutrino charge parity, mass ordering, and precision oscillation measurements.
- **Nucleon decay searches.**
- **Supernova physics:** measurement of ν_e flux.

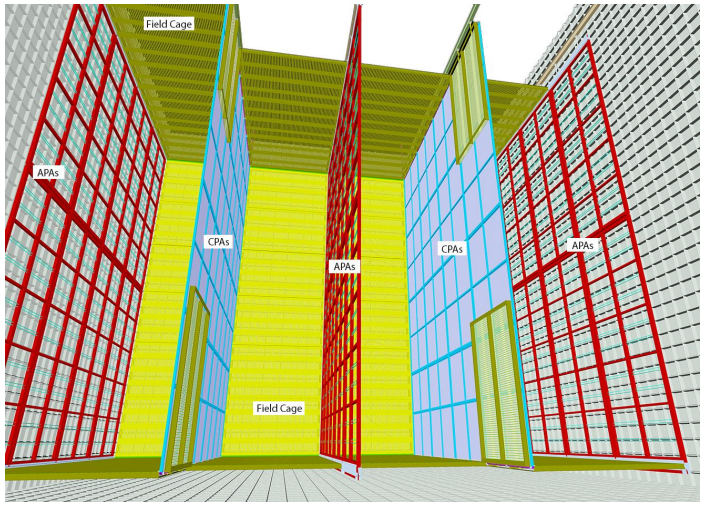
- To achieve all these goals, DUNE will use a **high-intensity neutrino beam** originating at Fermilab, a precision **near detector** for flux measurements, a 40 kt modular LAr **far detector** at Sanford Lab.

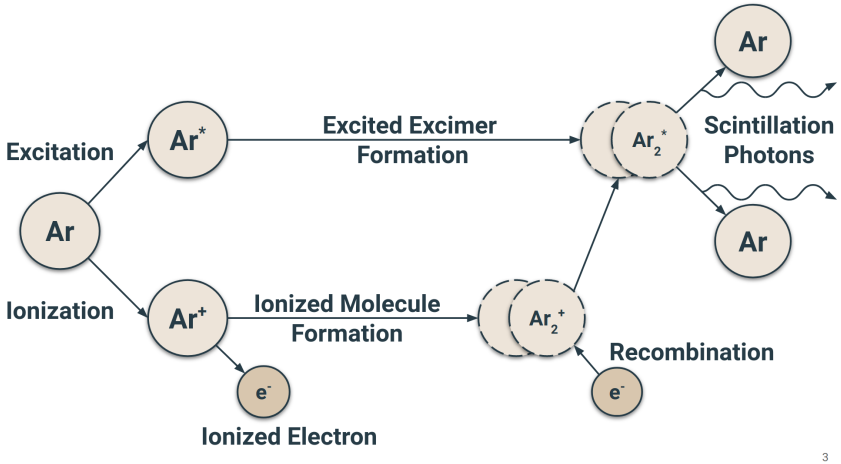
- See S. Prince's DUNE talk tomorrow for more!

Single Phase Far Detector Module

- The **DUNE far detector** (FD) will consist of four 10-kt LArTPC modules that collect charge and optical information.
  - Single- and dual-phase modules are being prototyped.
  - The first module deployed will be single-phase (SP).

- **1500 Photon Detector modules** per SP module (10 per APA).
  - 500 mounted on central APA frames, collect light from both sides.
  - 1000 mounted on frames near vessel walls.





DUNE SP IDR: arXiv:1807.10327

Physics with the PD system

- **Nucleon decay physics:** establishes event time (T0) needed for determining whether candidate events are contained and can be used to improve energy measurement.

- **Supernova neutrinos:** provides spatial information and improved energy reconstruction in addition to allowing for complimentary triggering on burst events.

- **Calorimetric energy reconstruction** for all events: can be used as a crosscheck or in combination with charge information to improve energy resolution.

- Can be used to **tag events with Michel electrons**, a valuable calibration sample for antineutrino flux.

PD System Requirements (a partial list)

Label	Description	Specification (Goal)	Rationale	Validation
SP-FD-3	Light yield	$>$ 20 PE/MeV (avg), $>$ 0.5 PE/MeV (min)	Gives PDS energy resolution comparable to that of the TPC for 5-7 MeV SN νs, and allows tagging of $>$ 99 % of nucleon decay backgrounds with light at all points in detector.	Supernova and nucleon decay events in the FD with full simulation and reconstruction.
SP-FD-4	Time resolution	$<$ 1 µs ($<$ 100 ns)	Enables 1 mm position resolution for 10 MeV SNB candidate events for instantaneous rate $<$ 1 $m^{-3}ms^{-1}$.	
SP-FD-15	LAr nitrogen contamination	$<$ 25 ppm	Maintain 0.5 PE/MeV PDS sensitivity required for triggering proton decay near cathode.	In situ measurment
SP-PDS-1	Clean assembly area	Class 100,000 clean assembly area	Demonstrated as satisfactory in ProtoDUNE-SP, and is the Deep Underground Neutrino Experiment (DUNE) assembly area standard.	ProtoDUNE-SP and in Fermilab materials test stand
SP-PDS-2	Spatial localization in y-z plane	$<$ 2.5 m	Enables accurate matching of photon detector (PD) and TPC signals.	SNB neutrino and nucleon decay (NDK) simulation in the FD

The Single Phase PD System

- The PD system must collect VUV scintillation light (127 nm) produced by ionizing particles traversing the TPC.

- Designed to have **no impact on fiducial volume.**
  - PD modules are placed in the inactive space between wire planes in the APAs.

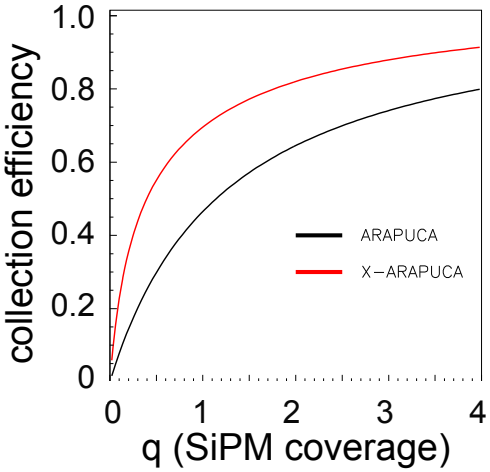
- Designed to **maximize VUV photon collection efficiency** while **minimizing the number of silicon photosensors**, necessary to make the system cost-effective.

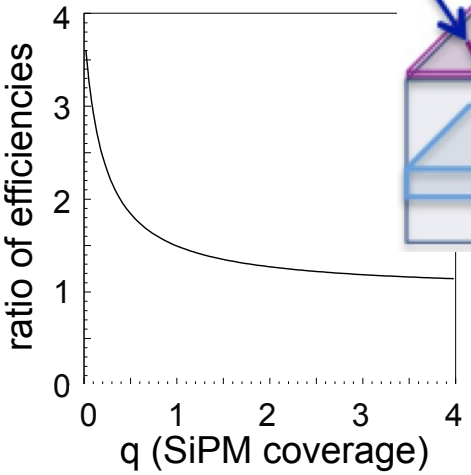
baseline system

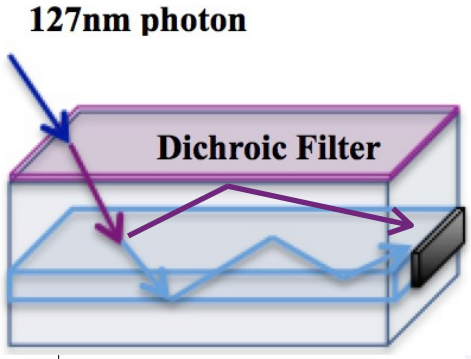
X-ARAPUCA	6 mm x 6 mm Hamamatsu MPPCs	active ganging of signals	commercial ultrasound ASICs
light collection	*photosensors*	*cold electronics*	*warm electronics*

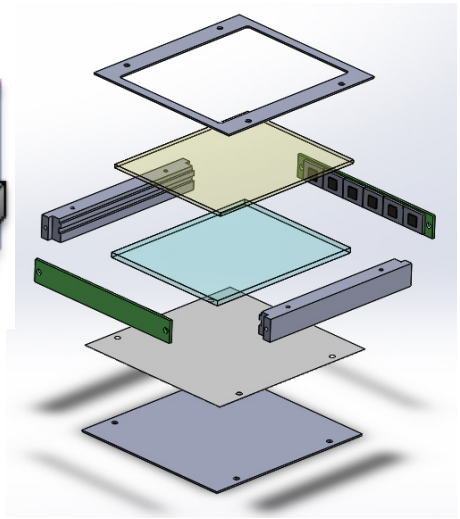
Light Collection: X-ARAPUCAs

- The **ARAPUCA**, a light trap: captures wavelength-shifted light inside highly reflective boxes.
- The **X-ARAPUCA** design makes use of **total internal reflection** to capture wavelength-shifted photons to further improve detection efficiency.
- Keys to an effective PD system in DUNE:
  - Efficient conversion of VUV photons to captured photons.
  - High fraction of captured photons incident on photosensors.
  - Efficient photosensors for converting photons into electric signals.



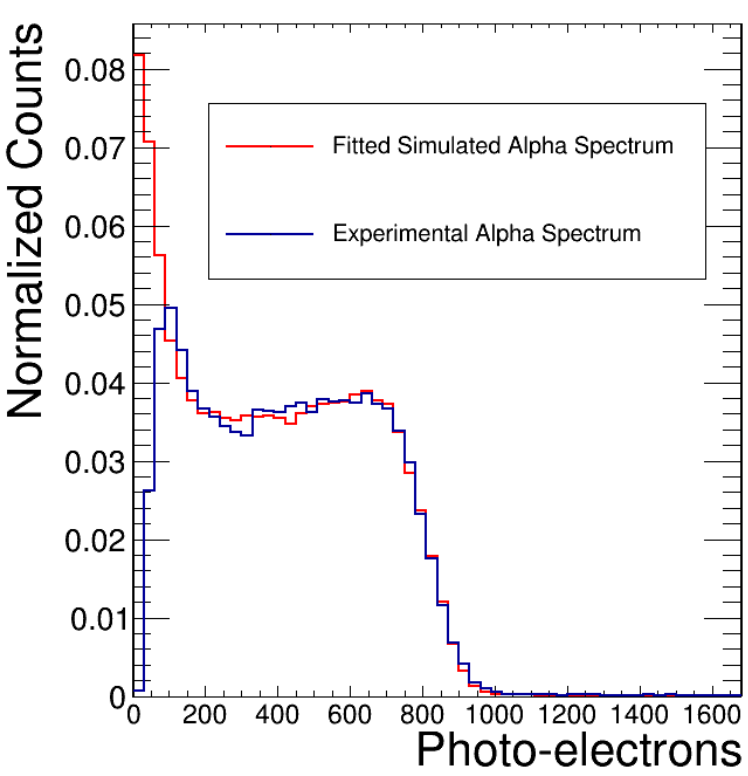






A.A. Machado *et al.*, J. Inst. **13**, C04026 (2018)

X-ARAPUCA Performance



- Total number of photoelectrons collected with an alpha source for a single-sided X-ARAPUCA.
- Compared number of detected photons to number of photons impinging on the photoncollector.
- The result yields a global photon collection efficiency of 3.5±0.5% for the X-ARAPUCA.

Photosensors: SiPMs

	Hamamatsu
Series part #	S13360
Vbr range	48 V to 58 V
Vop range	Vbr + 3 V
Temp. dependence	54 mV/K
Gain	1.7×10^6
Pixel size	50 μm
Sizes	2x2 mm
	3x3 mm
	6x6 mm
Wavelength	320 to 900 nm
PDE peak wavelength	450 nm
PDE @ peak	40%
DCR @0.5PE	2 to 6 MHz
Crosstalk	$< 3\%$
Afterpulsing	
Terminal capacitance	1300 pF
Lab experience	Good experiences from Mu2e and ARAPUCA

- Need to hold up mechanically and electrically in cryogenic environments for many years.
- **Baseline device:** 6mmx6mm Hamamatsu MPPCs.
  - 192 MPPCs per PD module with 48 MPPCs per X-ARAPUCA supercell.
  - In this configuration, 288,000 MPPCs per SP module.
- **Alternative:** device for operation in LAr developed by DarkSide in collaboration with FBK.

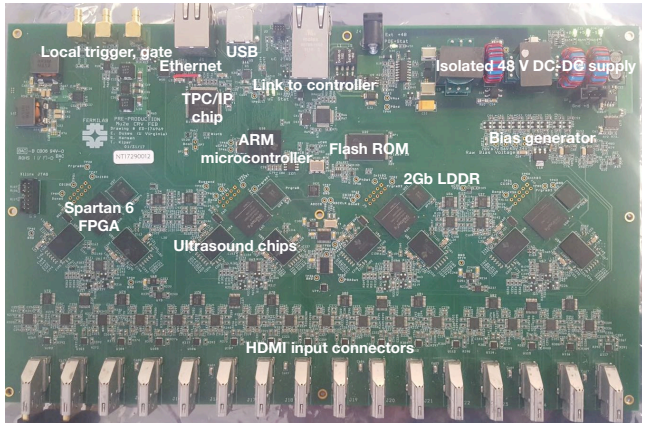
Cold Electronics: Active Ganging

- Four readout channels per PD module (one per X-ARAPUCA supercell).
- 48 SiPMs ganged together in a single differential output.
- Cold amplifier used to adjust MPPC output level prior to transmitting signal out of cryostat to warm readout electronics.
- Active ganging circuits developed at FNAL have demonstrated operation and SPE resolution at LAr temperatures.

Warm Digitizer: DAPHNE

- Cost-effective waveform digitization system developed by the Mu2e experiment that relies on **commercial ultrasound chips** (12-bit, 80MS/s).

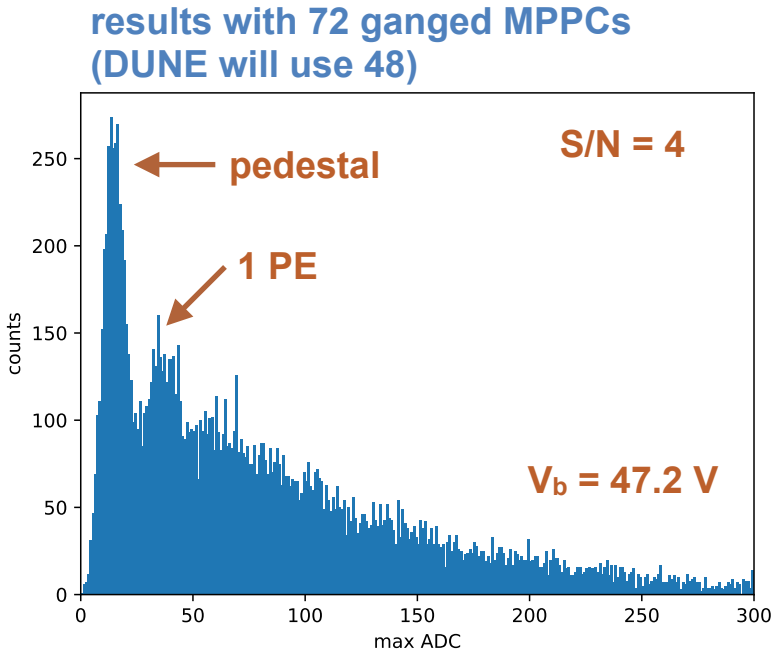
- **DAPHNE** (**D**etector electronics for **A**cquiring **PH**otons from **NE**utrinos) is an adaptation of this strategy to accommodate physics requirements of DUNE.
  - Newer FPGAs: upgrading Xilinx Spartan-6 to Xilinx Spartan-7 or Artix-7.
  - Will consider replacing the 12-bit TI AFE5807 ultrasound chip with the pinout-compatible 14-bit TI AFE5808 ultrasound chip.

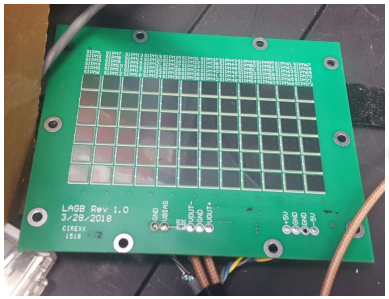


The existing Mu2e FEB, currently deployed at the ICEBERG Test Stand

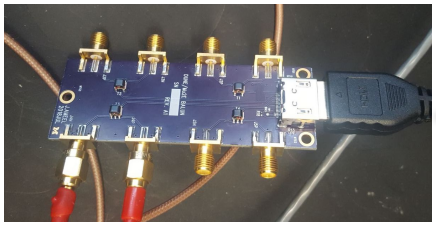
Mu2e FEB + active ganging @ FNAL

- The Mu2e electronics have been tested extensively with a variety of SiPMs/MPPCs and active/ passive ganging configurations.
- Demonstrated sensitivity to single PE signal and comparable signal-to-noise as the SSPs used in ProtoDUNE.

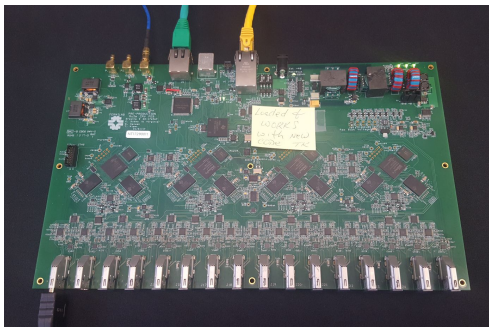




Active ganging board
(72 MPPCs)



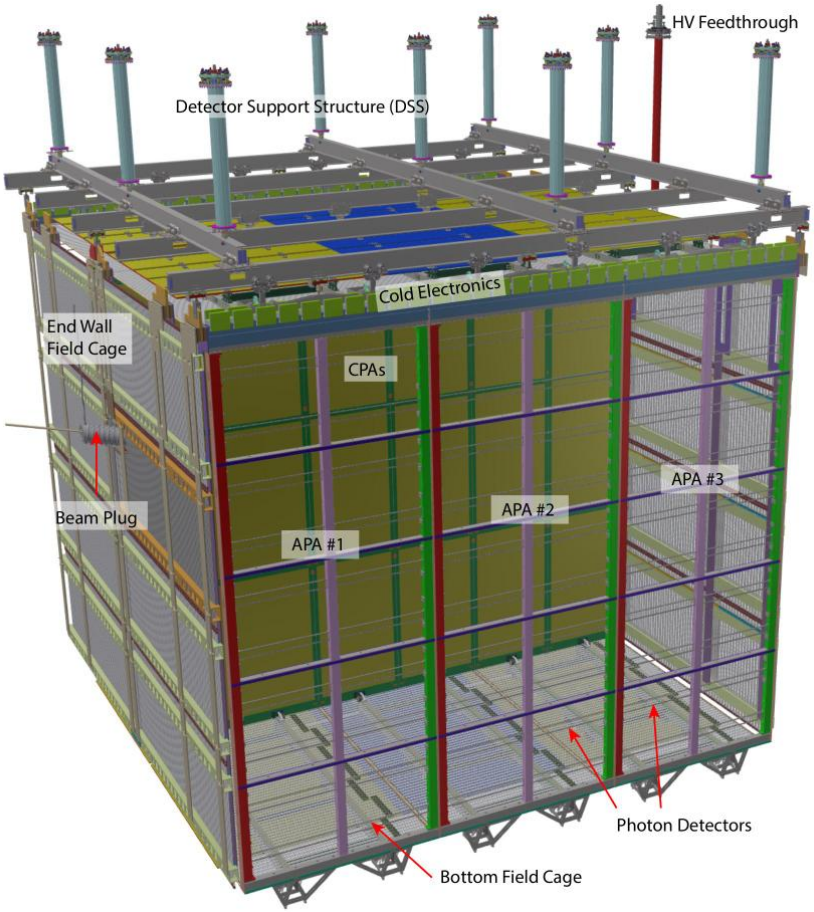
balun*
*for converting differential signals to single-ended signals



Mu2e FEB

ProtoDUNE-SP

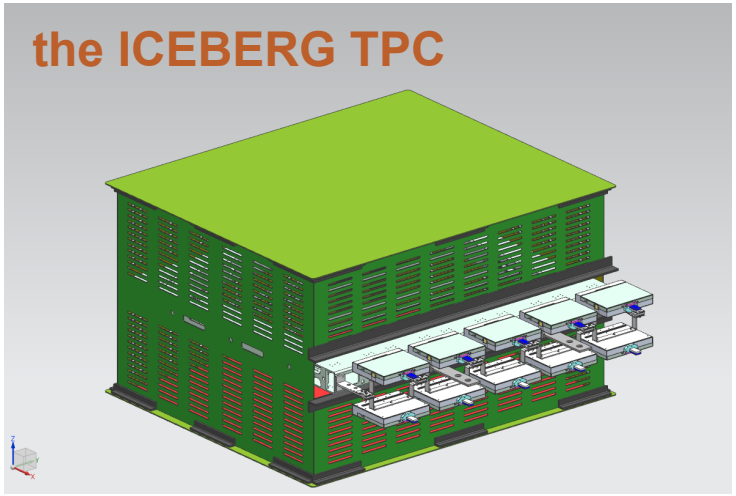
- Large-scale test of fully-instrumented PD prototype detector. **Operated with beam** in 2018.
- Three prototype photon collectors:
  - 29 double-shift light guides
  - 29 dip-coated light guide
  - 2 S-ARAPUCA arrays
- Confirmed superior detection **efficiency of S-ARAPUCA** modules.
- Demonstrated **timing capabilities of PD system.**
- Calibrated **S-ARAPUCA light yield** using both a UV-light calibration system and tagged cosmic rays.
- Plans to test X-ARAPUCA design in a future run.

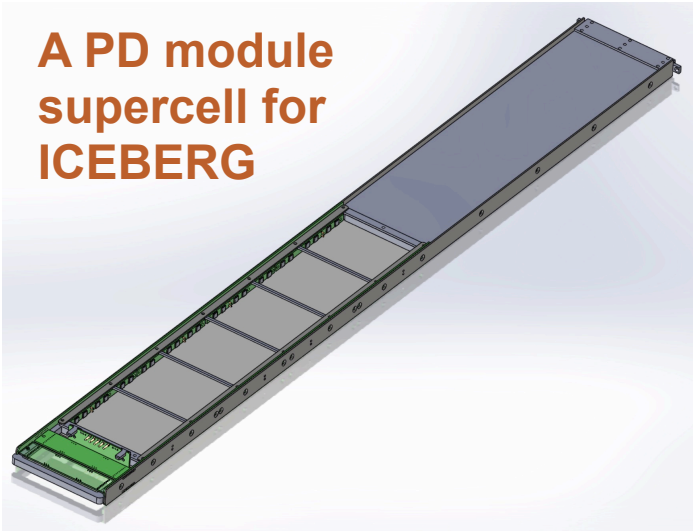


ProtoDUNE SP TDR: arXiv:1706.07081

ICEBERG Test Stand

- Small scale TPC using a reduced-size version of the FD APA design.
- Initial cosmic data has been collected.
- Allows comparisons between the ProtoDUNE SSP and Mu2e-based warm readout electronics.
- Currently instrumented with one S-ARAPUCA and one X-ARAPUCA supercell.
- Will be used for future tests of warm and cold readout electronics prototypes.





Other testing environments

- **SBND (2020/2021):** large-scale operational testing of X-ARAPUCAs similar to those designed for DUNE and demonstration of DAQ integration with current Mu2e warm readout electronics.

- **ProtoDUNE-2 (2021/2022):** end-to-end test of finalized PD system.
  - Full-size X-ARAPUCA modules.
  - 48-MPPC active ganging cold electronics.
  - Warm readout with Mu2e-based DAPHNE system including integration with TPC DAQ.
  - Tests of two candidate photosensors.

Summary

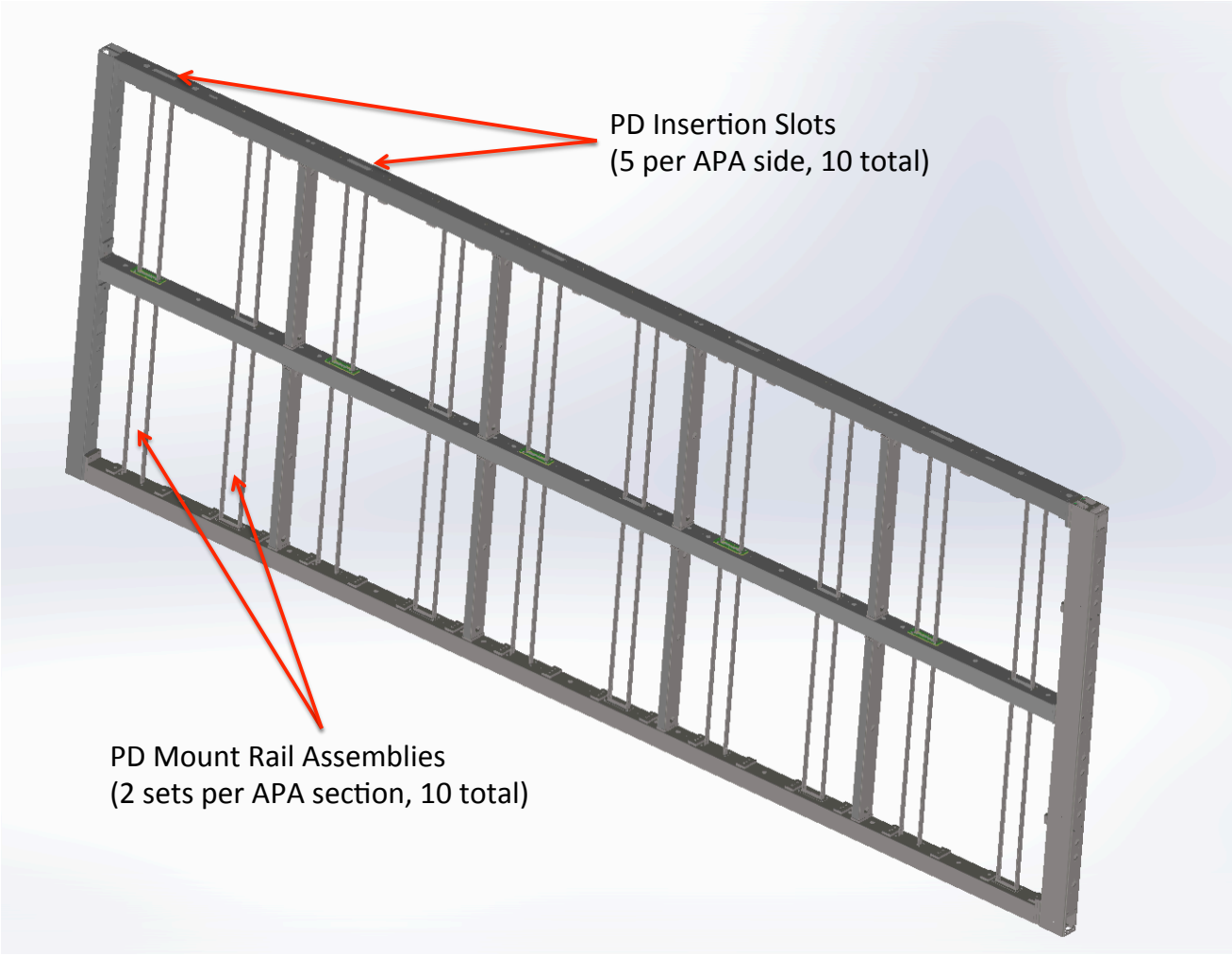
- The DUNE photon detection system is critical for achieving nucleon decay and supernova physics goals.
- The PD system will also provide valuable crosschecks to charge readout, supplemental calibration methods and improved time and energy resolution.
- Extensive testing and validation of component designs is underway.

Extra Slides

SP FD PDS Baseline Configuration

Component	Description	Quantity
Light collector	X-ARAPUCA	10 modules per APA; 1500 total (1000 single-sided; 500 double-sided)
Photosensor	Hamamatsu MPPC 6 mm×6 mm	192 SiPM per module; 288,000 total
SiPM signal summing	6 passive × 8 active	4 circuits per module; 6000 total
Readout electronics	Based on commercial ultrasound chip	4 channels/module; 6000 total
Calibration and monitoring	Pulsed UV via cathode-mounted diffusers	45 diffusers/CPA side; 180 diffusers for 4 CPA sides

APA Frame


PD Insertion Slots
(5 per APA side, 10 total)
PD Mount Rail Assemblies
(2 sets per APA section, 10 total)

Photosensors

Table 5.3: Candidate Photosensors Characteristics.

	Hamamatsu (Baseline)	Hamamatsu-2	FBK
Series part #	S13360	S14160	NUV-HD-LF
V_{br} (typical)	50 V to 52 V	36 V to 38 V	31 V to 33 V
V_{op} (typical)	V_{br}+3 V	V_{br}+2.5 V	V_{br}+3 V
Temperature dependence of V_{br}	54 mV/K	35 mV/K	25 mV/K
Gain at V_{op}(typical)	1.7×10^6	2.5×10^6	0.75×10^6
Pixel size	50 μm	50 μm	25 μm
Size	6 mm x 6 mm	6 mm x 6 mm	4 mm x 4 mm
Wavelength	320 to 900 nm	280 to 900 nm	280 to 700 nm
PDE peak wavelength	450 nm	450 nm	450 nm
PDE at peak	40%	50%	50%
DCR at 0 · 5PE	$< 50\,\text{kHz} \cdot \text{mm}^{-2}$	$< 100\,\text{kHz} \cdot \text{mm}^{-2}$	$< 25\,\text{kHz} \cdot \text{mm}^{-2}$
Crosstalk	$< 3\%$	$< 7\%$	$< 3\%$
Afterpulsing			
Terminal capacitance	$35\,\text{pF} \cdot \text{mm}^{-2}$	$55\,\text{pF} \cdot \text{mm}^{-2}$	$50\,\text{pF} \cdot \text{mm}^{-2}$
Lab experience	Mu2e and DUNE prototypes		Darkside